INTRODUCTION TO VISIBILITY

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Introduction

A definition of visibility, as it relates to management of the many visual resources found in national parks, is a complex and difficult idea to address. Should visibility be defined in strictly technical terms which concern themselves with exact measurements of illumination, threshold contrast and precisely measured distances? Or is visibility more closely allied with value judgements of an observer viewing a scenic vista?

Historically "visibility" has been defined as "the greatest distance at which an observer can just see a black object viewed against the horizon sky." An object is usually referred to as at threshold contrast when the difference between the brightness of the sky and the brightness of the object is reduced to such a degree that an observer can just see the object. Much effort has been expended in establishing the threshold contrast for various targets under a variety of illumination and atmospheric conditions. An important result of this work is that threshold contrast for the eye adapted to daylight changes very little with background brightness but is strongly dependent upon the size of the target and the time spent looking for the target.

However, visibility is really more than being able to see a black object at a distance for which the contrast reaches a threshold value. Coming upon a mountain such as one of those shown in Figures Ia and Ib an observer does not ask, "How far do I have to back away before the vista disappears?" Rather, the observer will comment on the color of the mountain, on whether geological features can be seen and appreciated, or on the amount of snow cover resulting from a recent storm system. Approaching landscape features such as those shown in Figures Ic and Id the observer may comment on the contrast detail of nearby geological structures or on shadows cast by overhead clouds.

Visibility is more closely associated with conditions which allow appreciation of the inherent beauty of landscape features. It is important to be able to see and appreciate the form, contrast detail, and color of near and distant features. Because visibility includes psychophysical processes and concurrent value judgements of visual impacts, as well as the physical interaction of light with particles in the atmosphere, it is necessary to:

- understand the psychological process involved in viewing a scenic resource,
- specify and understand the value that an observer places on visibility, and
- be able to establish a link between the physical and psychological processes.

Whether we define visibility in terms of visual range or in terms of some parameter more closely related to how visitors perceive a visual resource, it is necessary to understand what constituents in the atmosphere reduce visibility as well as the origins of those constituents.

Figure la
The farthest scenic feature is the 130 km. distant Navajo Mountain, as seen from Bryce Canyon National Park.

Figure lb
The La Sal Mountains, as seen from the Colorado River, are a dominant form on the distant horizon.

Scientists know that introduction of particulate matter and certain gases into the atmosphere interfers with the ability of an observer to see landscape features. Monitoring, modeling, and controlling sources of visibility-reducing particulate matter and gases depend on scientific and technical understanding of how these pollutants:

- interact with light,
- transform from a gas into particles that reduce visibility,
- are dispersed in local canyons and valleys, and
- are transported from a source, over hundreds of kilometers, to a receptor such as one of the national parks.

Scientific understanding of some of these issues is more complete than of others. The goal of this publication is to assist the reader in developing basic knowledge of those concepts for which there is an understanding and to indicate the areas which need further research.

Figure Ic
This view in Canyonlands National Park shows the highly textured foreground canyon walls against the backdrop of the La Sal Mountains. The La Sals are 50 km. away from the observation point.

Figure Id
Bryce Canyon as seen from a hiking trail just below Bryce Point. Notice the highly textured and brightly colored foreground features.

Figure I
Figures Ia through Id show that, from a visual resource point of view, visibility is not how far a person can see, but rather the ability of an observer to clearly see and appreciate the many and varied scenic elements in each vista.

SECTION ONE THE NATURE OF LIGHT

One of our principal contacts with the world around us is through light. Not only are we personally dependent on light to carry visual information, but much of what we know about the stars and the solar system is derived from light waves registering on our eyes and on optical instruments.

Light can be thought of as waves, and to a certain extent they are analogous to water and sound waves. Figure 1.1 is a schematic representation of water waves with the distance from crest to crest denoted as one wavelength.

Similar oscillations of electric and magnetic fields are called electromagnetic radiation. Ordinary light is a form of electromagnetic radiation, as are x-rays, ultraviolet, infrared, radar, and radio waves. All of these travel at approximately 300,000 km./sec. (186,000 mi./sec.) and only differ from one another in wavelength. Figure 1.2 is a schematic representation of the electromagnetic spectrum with the visible portion shown in color to emphasize the portion of the spectrum to which the human eye is sensitive. The visible spectrum is white light separated into its component wavelengths or colors. The wavelength of light, typically measured in terms of millionths of a meter (microns), extends from about 0.4 to 0.7 micron.

Waves of all kinds, including light waves, carry energy. Electromagnetic energy is unique in that energy is carried in small, discrete parcels called photons. Schematic representations of a blue, green, and red photon are shown in Figure 1.3. Blue, green,

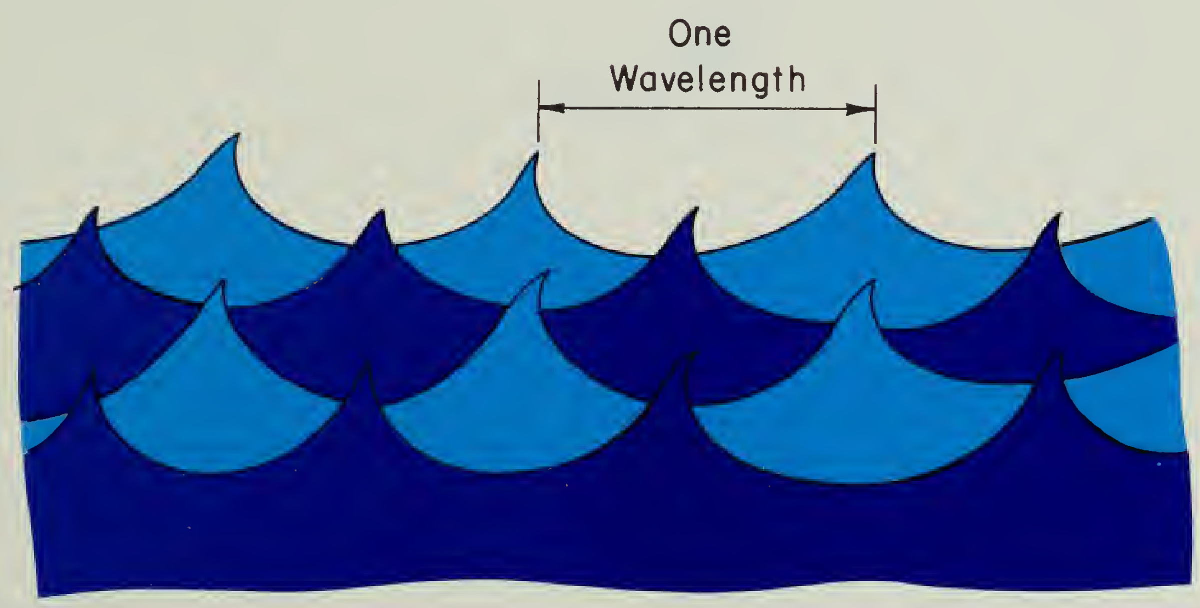


Figure 1.1
Water waves can be used to show the concept of wavelengths. A wavelength is defined as the distance from one crest to the next.

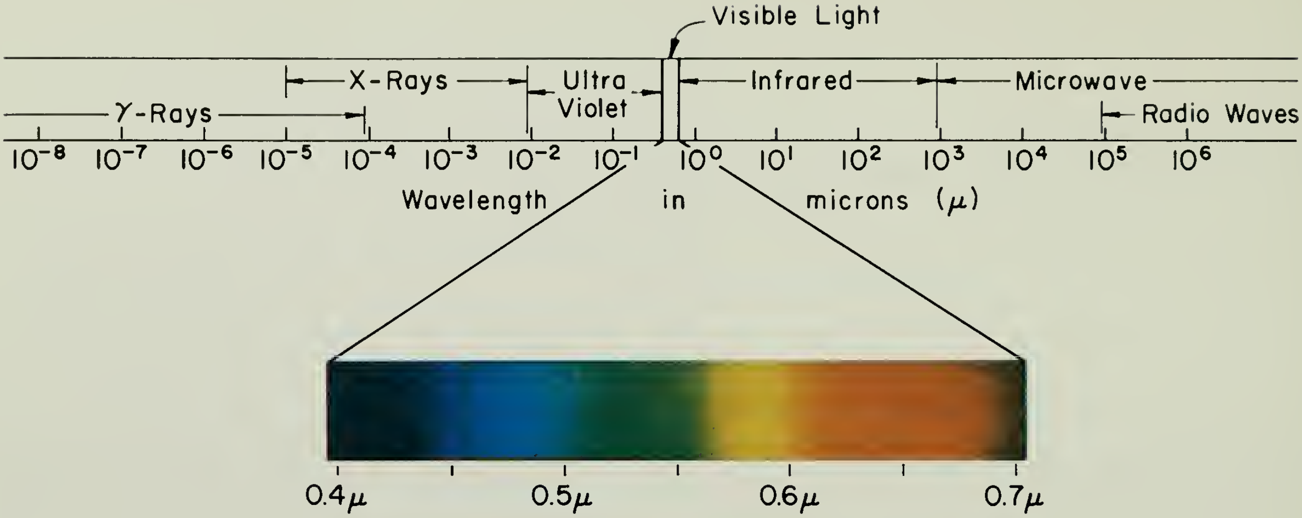


Figure 1.2
Vibrations of electric and magnetic fields are referred to as electromagnetic radiation. This diagram shows the wavelengths of various types of electromagnetic radiation including visible light. The wavelength of the visible spectrum varies from 0.4 micron (blue) to 0.7 micron (red). One micron equals one millionth of a meter.

and red photons have wavelengths of around 0.45, 0.55 and 0.65 micron respectively. The color properties of light depend on its behavior both as waves and as particles.

Colors created from white light by passing it through a prism are a result of the wave-like nature of light. A prism separates the colors of light by bending (refracting) each color to a different degree. Colors in a rainbow are the result of water droplets, acting like small prisms, dispersed through the atmosphere. Each water droplet refracts light into the component colors of the visible spectrum.

More commonly, the colors of light are separated in other ways. When light strikes an object certain color photons are captured by molecules in that object. Different types of molecules capture photons of different colors. The only colors we see are those photons that the surface reflects. For instance, chlorophyll in leaves capture photons of red and blue light and allow green photons to bounce back, thus providing the green appearance of leaves. Nitrogen dioxide, a gas emitted into the atmosphere by combustion sources, captures blue photons. Consequently, nitrogen dioxide gas tends to look reddish brown. Figure 1.4 is an example of an eggshell reflecting all wavelengths of light. The eye perceives the eggshell to be white. An apple, on the other hand, reflects mostly red light while absorbing all others, so the apple, to an eye-brain system, appears to be red.

For all practical purposes, in visibility, it is most convenient to think of light as being made of small colored particles. The following sections of this document will discuss more specifically how these "light" particles interact with atmospheric particulate matter and gases.

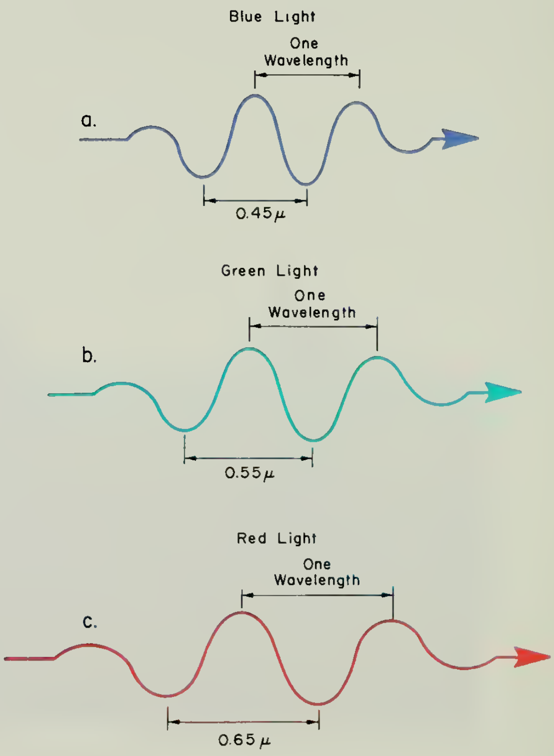


Figure 1.3a, b, and c
At times light can exhibit either wave-like or particle-like characteristics. Light can be thought of as consisting of bundles of vibrating electric and magnetic waves. These bundles of energy are called photons, and the wavelengths of radiant energy making up the photon determine its "color." Figures 1.3a, 1.3b and 1.3c schematically show a blue, green and red photon.

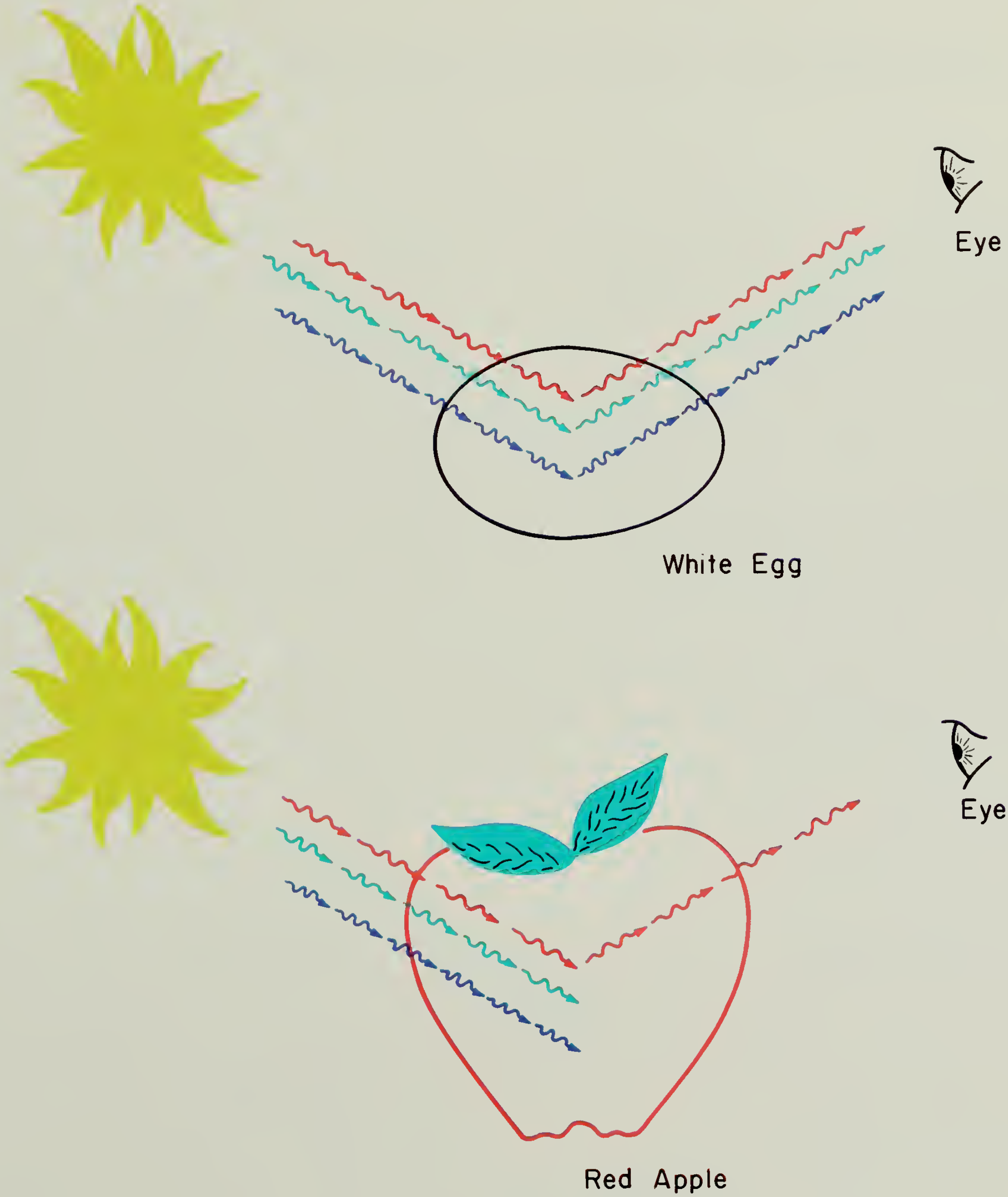


Figure 1.4

Why some objects appear white while others appear colored. White light, which is composed of all "colors" of photons, strikes an object. If the object is white, photons of every color are reflected. However, if some photons are absorbed while others are reflected, the object will appear to be colored; a red apple, for instance, reflects red photons and absorbs all others.

SECTION TWO INTERACTION OF LIGHT AND PARTICLES

A photon of light is said to be scattered when it is received by a particle and re-radiated at the same wavelength in any direction. Visibility degradation results from light scattering and absorption by atmospheric particles and gases which are nearly the same size as the wavelength of the light. Particles somewhat larger than the wavelength of light can scatter light as a result of a combination of the first three phenomenon shown schematically in Figures 2.1a, 2.1b, and 2.1c. Figure 2.1a shows diffraction, a phenomenon whereby radiation is bent to ''fill in the shadow'' behind the particle. Figure 2.1b depicts light being bent (refracted) as it passes through the particle. A third effect resulting from slowing a photon is a little difficult to understand. Consider two photons approaching a particle, each vibrating ''in phase'' with one another. One passes by the particle, retaining its original speed, while the other, passing through the particle, has its speed altered. When this photon emerges from the particle, it will be vibrating ''out of phase'' with its neighbor photon; when it vibrates up, its neighbor will vibrate down. As a consequence, they interfere with each other's ability to propagate in certain directions (Figure 2.1c).

Figure 2.1d indicates how a photon can be absorbed photon is transferred to internal molecular energy or heat energy. In the absorption process the photon is not redistributed into space; the photon ceases to exist.

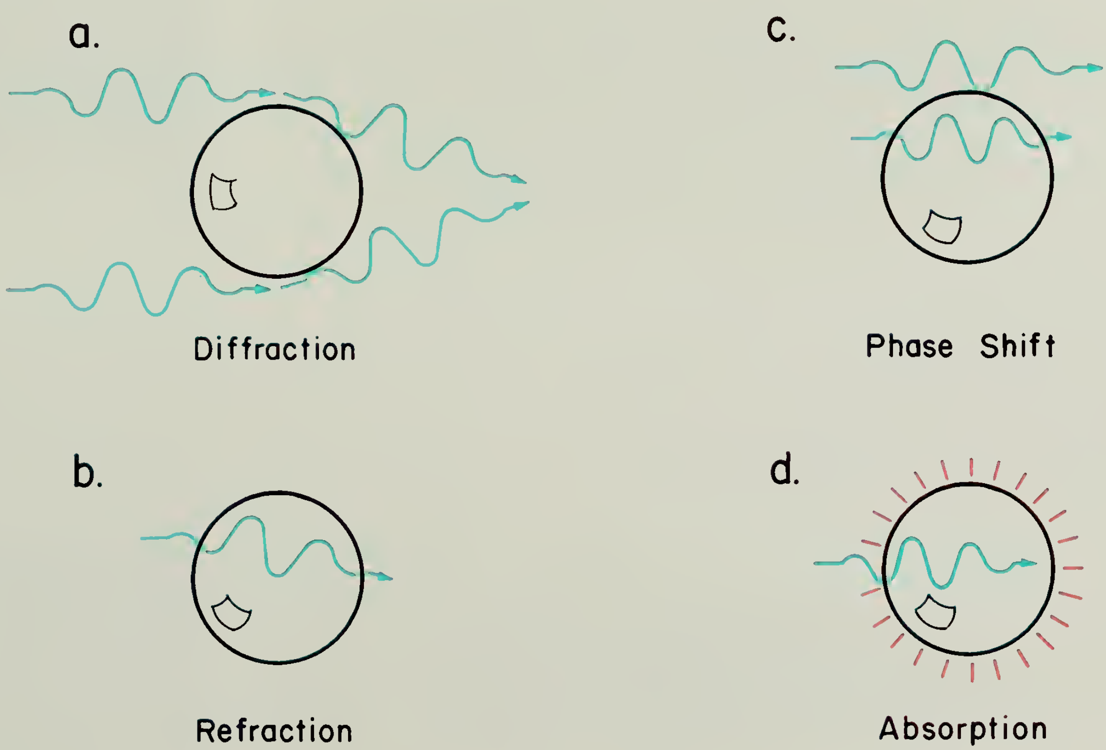


Figure 2.1a, b, c, and d
Large particle light scattering and absorption. Diffraction (2.1a) and refraction (2.1b) combine to "bend" light to "fill in the shadow" behind the particle. Diffraction, an edge effect, causes photons passing very close to a particle to bend into the shadow area; refraction is a result of the light wavefront slowing down as it enters the particle. While the photon is within the particle its wavelength is also shortened. Thus, when it emerges from the particle it may vibrate out of phase with adjacent photons and interfere with their ability to propagate in a pre-prescribed direction. This effect (phase shift) is shown in Figure 2.1c. As a fourth possibility, the photon may be absorbed by the particle (Figure 2.1d). In this case the internal energy of the particle is increased. The particle may rotate faster or its molecules may vibrate with greater amplitude.

The efficiency with which a particle can scatter light and the direction in which the incident light is redistributed are dependent on all four of these effects. Photons can be scattered equally in all directions (isotropic scattering), but in most instances photons are scattered in a forward direction.

Figures 2.2 and 2.3 show the distribution of scattered light for particles which are respectively much smaller and much larger than the wavelength of light. If the particles are small (such as the air molecules themselves) the amounts of light scattered in the forward and backward directions are nearly the same. This type of scattering is referred to as rayleigh scattering. As the particle increases in size more light tends to scatter in the forward direction until for large particles nearly 100% of the incident photons end up being scattered in the forward direction.

The fact that light scatters preferentially in different directions as a function of particle size is extremely important in determining the effects that atmospheric particulates have on a visual resource. The angular relationship between the sun and observer in conjunction with the size of particulates determines how much of the sunlight is redistributed into the observer's eye.

The effect of particulates on visibility is further complicated by the fact that particulates of different sizes are able to scatter light with varying degrees of efficiency. It is of interest to investigate the efficiency with which an individual particle can scatter light. The efficiency factor is expressed as a ratio of a particle's effective cross section to its actual cross section. Figure 2.4 shows how this efficiency varies as a function of particle size. Very small particles and molecules are very inefficient at scattering light. As a particle increases in size it becomes a more efficient light scatterer until, at a size that is close to the wavelength of the

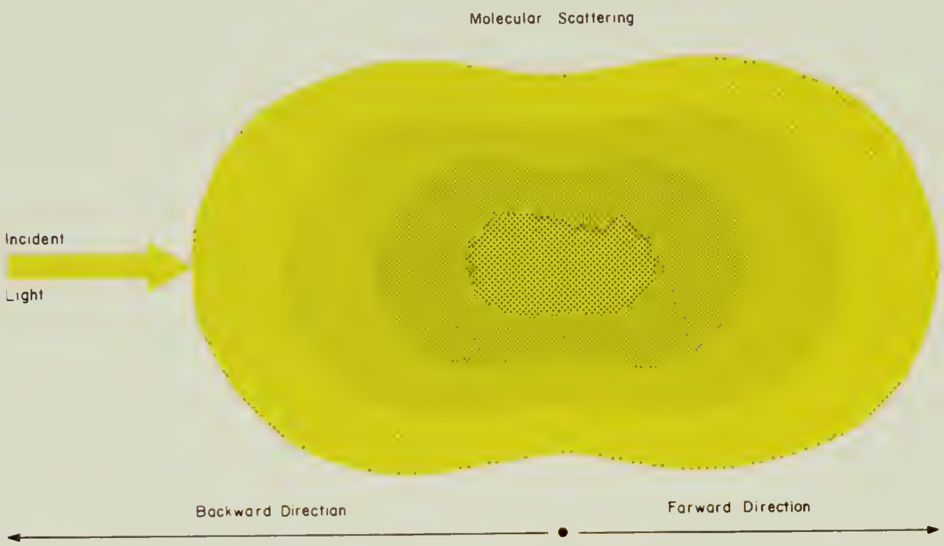


Figure 2.2
Light interacts with a particle through the processes shown in Figure 2.1. If the particle is very small the net result of the interaction process is to redistribute incident light in a way shown in the above diagram. Equal numbers of photons are scattered in the forward and backward directions and about one-half of the number of forward scattered photons are directed to the sides (90 degree scattering).

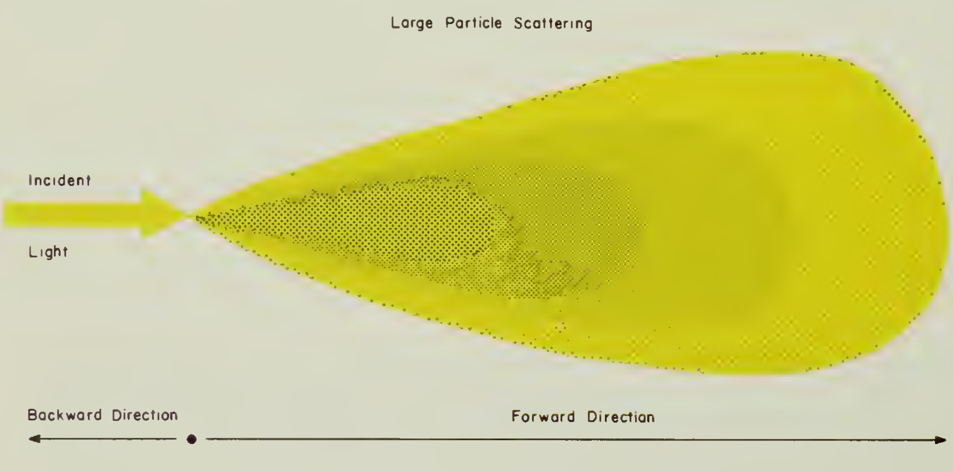


Figure 2.3
If the particle is large, most of the incident light is scattered in the forward direction.

incident light, it can scatter more light than a particle five times its size. Even particles which are very large scatter light as if they were twice as big as they actually measure. Each of these particles removes twice the amount of light intercepted by its geometric cross-sectional area.

Figure 2.5 shows the relative amounts of small and large particles found in the atmosphere. The green line is a typical mass size distribution of particles. The y-axis is the amount of mass in a given size range; the x-axis is particle size measured in microns. Notice the two-humped, or bi-modal, curve. Those particles less than about 2 microns are referred to as fine particles and particles larger than 2 microns are called coarse particles.

The red curve is the corresponding amount of light scattering that can be associated with each size range. Even though there is less mass concentrated in the fine mode, it is the fine particulates that are the most responsible for scattering light. This is because fine particles are more efficient light scatterers than large particles, and because there are more of them, even though their total mass is less than the coarse mode. Consequently it is the origin and transport of fine particles that is of greatest concern when assessing visibility impacts.

It is this scattering phenomenon that is responsible for the colors of hazes in the sky. The sky is blue because blue photons, with their shorter wavelengths, are nearer the size of the molecules that make up the atmosphere than are their green, orange, and red counterparts. Thus blue photons are scattered more efficiently by air molecules than red photons, and as a consequence, the sky looks blue.

Figure 2.4
The relative efficiency with which particles of various sizes scatter light. The green line corresponds to the scattering efficiency of molecules. The red and blue lines show the efficiency with which fine and coarse particles scatter light. Note that fine particles (0.1 micron to 1.0 micron) are more efficient at scattering light than are either molecules or coarse particles.

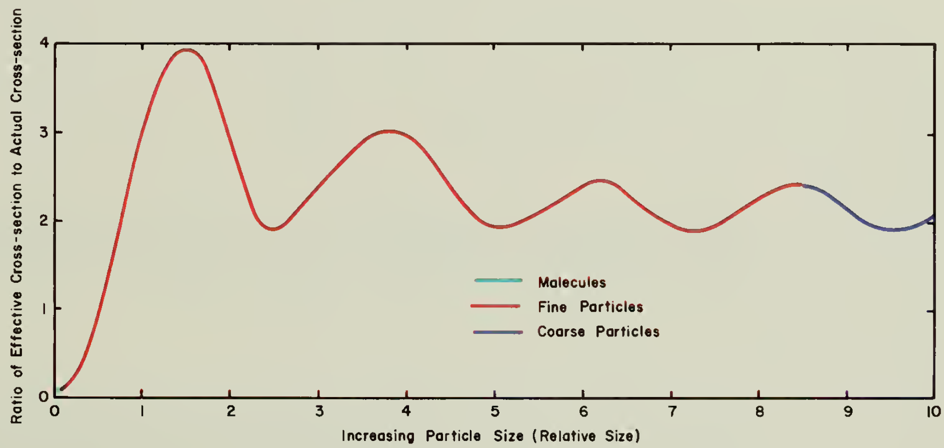


Figure 2.5
The green line shows the relative amount of mass typically found in a given particle size range. The red line shows the relative amount of particle scattering associated with that mass. Note that even though mass is associated with coarse particles, it is the fine particles that are primarily responsible for scattering light.

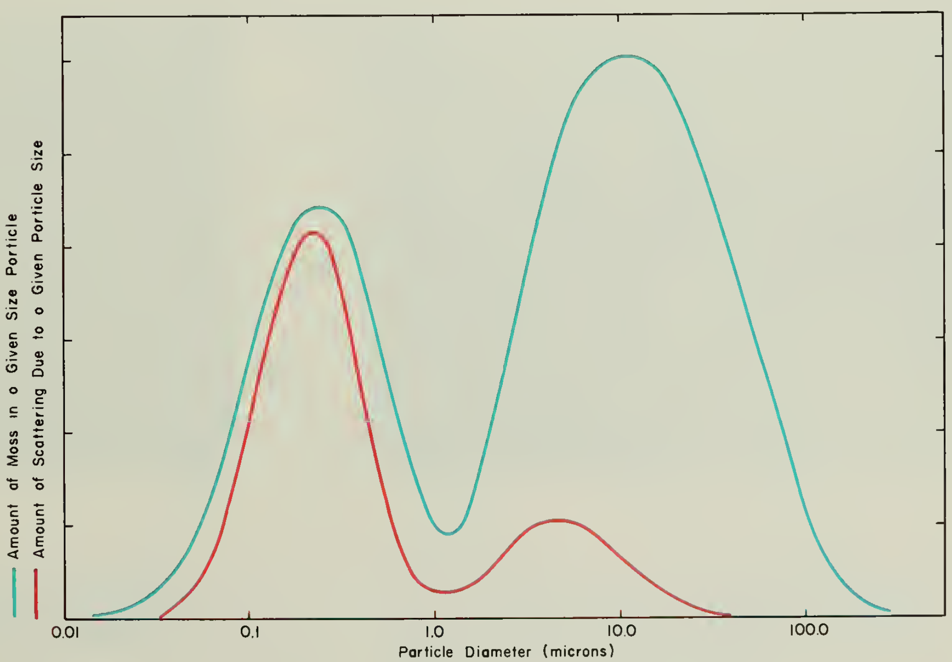


Figure 2.6 schematically shows what happens when the red, blue, and green photons of white light strike small particles. Only the blue photons are scattered because scattering efficiency is greatest when the size relationship of photon to particle is close to 1:1. The red and green photons pass on through the particles. To an observer standing to the side of the particle concentration the haze would appear to be blue. Figure 2.7 shows what happens when the particles are about the same size as the incoming radiation. All photons are scattered equally, and the haze appears to be white or gray.

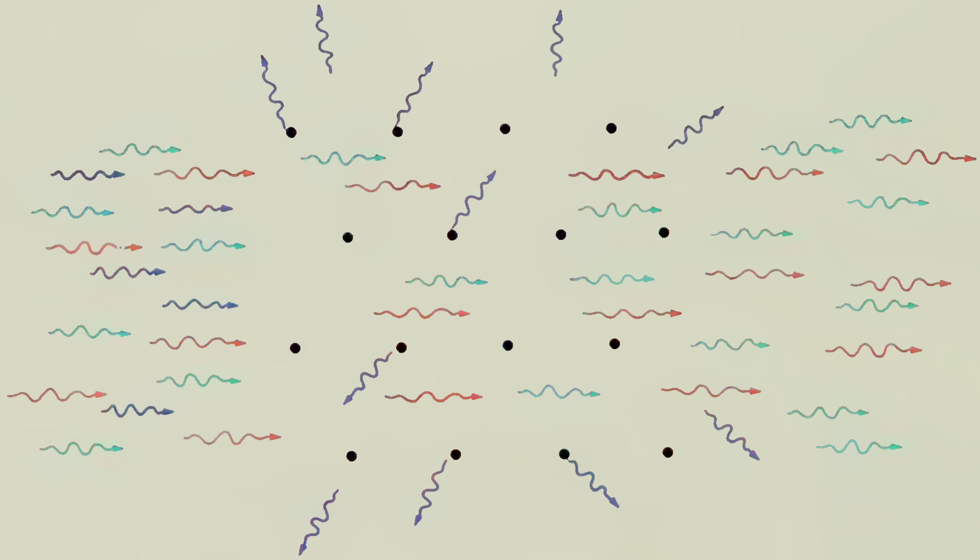


Figure 2.6
As a beam of white light (consisting of all "colored" photons) passes through a haze made up of small particles, it is predominantly the blue photons which are scattered in various directions.

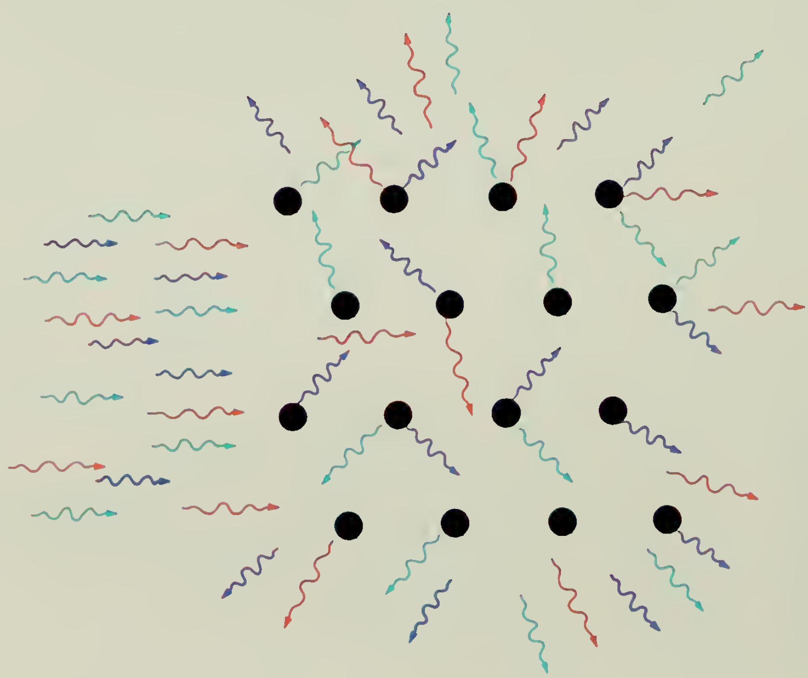


Figure 2.7
When particles are near or larger than the wavelength of the incident light, photons of all colors are scattered out of the beam path.

Figure 2.8 is a similar diagram of white light passing through a concentration of nitrogen dioxide (NO_2) molecules. Blue photons are absorbed, so a person standing in the beam of light would see it as being reddish brown (i.e. without blue) rather than white.

Figure 2.9 further exemplifies the relationship of particle size and the color of scattered light. Figure 2.9a shows a lighted cigarette held in a strong beam of white light. Notice that the smoke appears to have a bluish tinge to it. One can conclude that these particles must be quite small because they are scattering more blue than green or red photons. Figure 2.9b is smoke from the same cigarette. However, the smoke in Figure 2.9b has been held in the author's mouth for a few seconds. The inside of a person's mouth is humid, and smoke particles have a high affinity for water vapor. These hygroscopic particles tend to grow to sizes that are near the wavelengths of light and thus scatter all wavelengths of light equally. Scattered photons having wavelengths that extend over the whole visible spectrum are, of course, perceived to be white or gray.

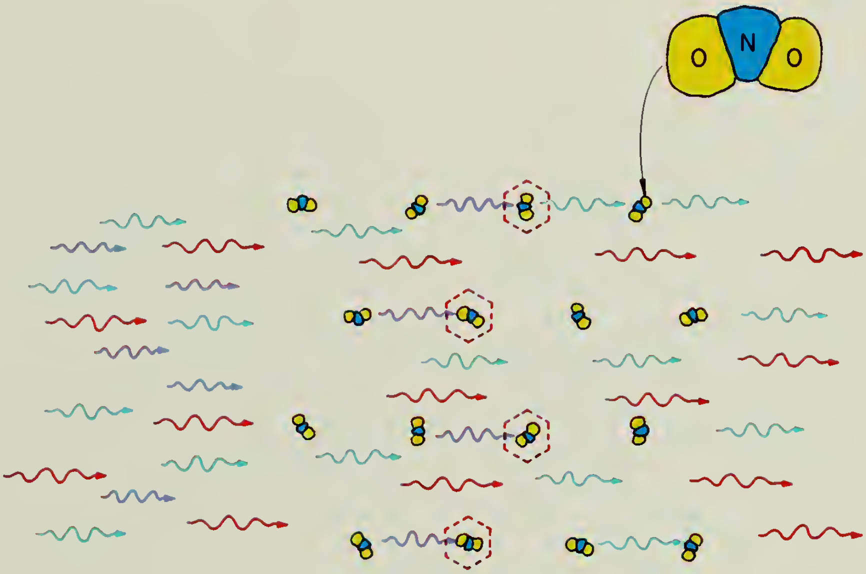


Figure 2.8
An atmosphere containing nitrogen dioxide (NO_2) will tend to deplete the number of blue photons through the absorption process. As a result, white light will tend to look reddish or brownish in color after passing through a nitrogen dioxide haze.

Figure 2.9a
This photograph shows the color of small particles that have been illuminated by white light. Because the smoke appears blue it can be concluded that the scattering particles must be quite small, less than the wavelength of visible light.

Figure 2.9b
A photograph of similar particles after they have been allowed to grow in a humid environment. Note that as a result of equal scattering of all photon colors, these larger particles appear white instead of blue.

SECTION THREE MEASUREMENT OF SCATTERING AND ABSORPTION

The scattering coefficient is a meaure of the ability of particles to scatter photons out of a beam of light. The absorption coefficient indicates how many photons are absorbed. Each parameter is expressed as a number proportional to the amount of photons scattered or absorbed per distance. The sum of scattering and absorption is referred to as extinction or attenuation.

Figure 3.1 is a schematic diagram showing a beam of light made up of photons with varying wavelengths that is incident on a concentration of particles and absorbing gas. Knowing the number of photons incident on a concentration of particles and measuring the number of photons successfully passing through the particulate concentration, it is possible to calculate the number of photons scattered and absorbed. The instrument which measures extinction (sum of scattering and absorption) is known as a transmissometer.

The light source is usually an incandescent lamp, and the receiver is a telescope fitted with an appropriate detector. The light source and detector can be placed 30 kilometers apart, and the measurement is usually referred to as long path measurement.

A similar light source-detector configuration can be used to meaure just the scattering ability of particles and gases. If the detector is placed parallel to the incident photons only those photons that are scattered will be detected. This type of instrument is called a

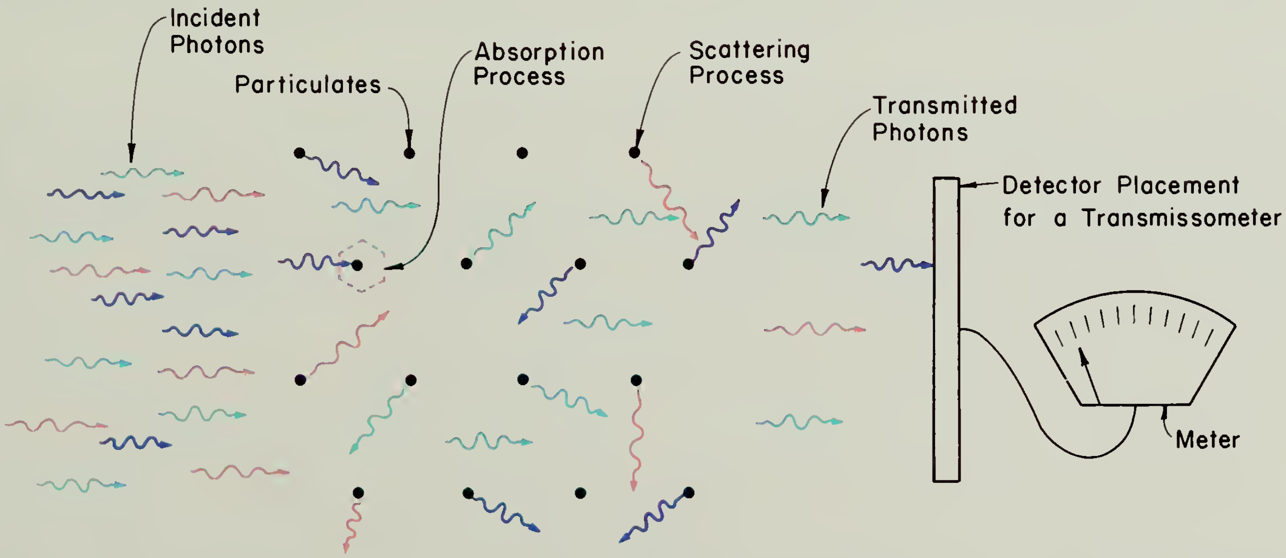


Figure 3.1
Placement of a light source and detector as shown in Figure 3.1 is known as a transmissometer. As photons pass through a concentration of particles and gases they are either scattered out of the light path or they are absorbed. Thus a detector placed as indicated measures only those photons that are transmitted the length of the light path. Because this instrument is sensitive to both scattering and absorption it can be callbrated to measure the extinction coeffiecient.

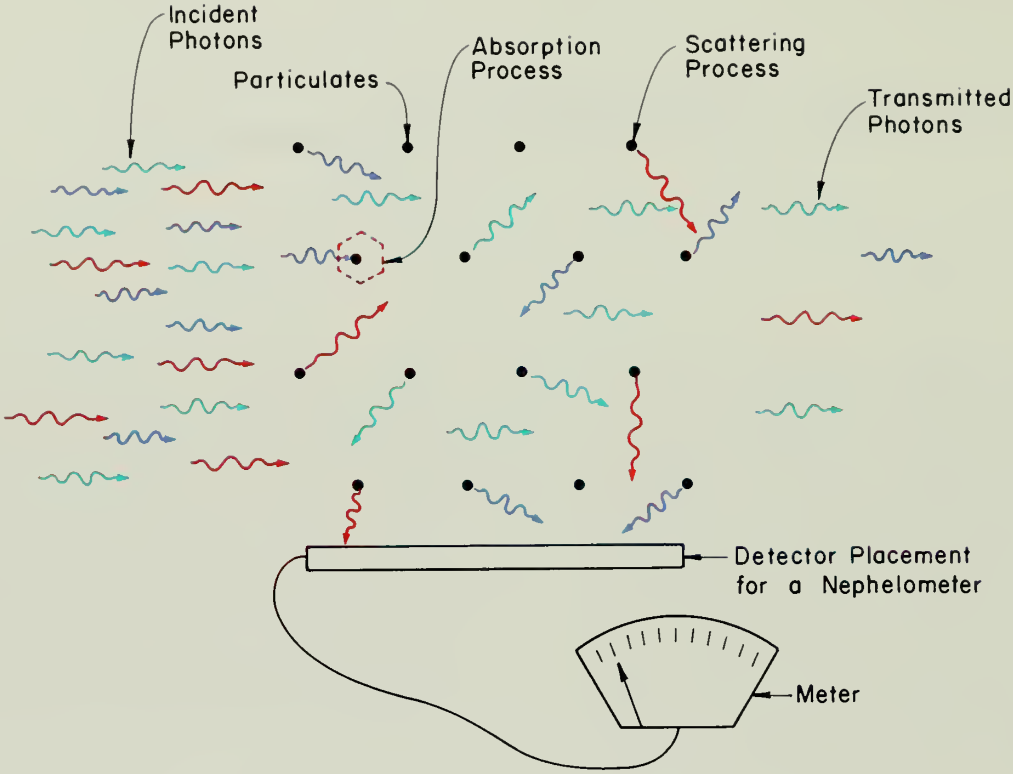
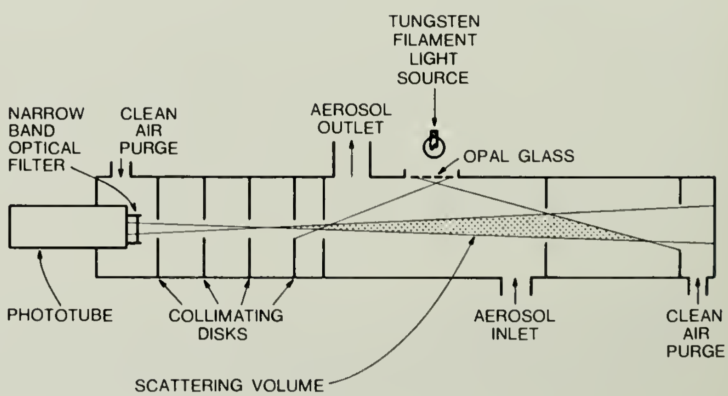


Figure 3.2a
Placement of a detector for the measurement of the number of photons scattered by a concentration of particles and gas.

nephelometer (Figure 3.2a). If the detector is so aligned as to measure scattering in only one direction it is referred to as a polar nephelometer. On the other hand, if all photons scattered in forward, side, and back directions are allowed to hit the detector, the instrument is referred to as an integrating (summing) nephelometer. The instrument is usually constructed in such a way as to have the sampling chamber and light source confined to a small volume so that the instrument makes a "point" or localized measurement of scattering. Figure 3.2b shows the configuration of light source, detector, and electronics for a typical, commercially available nephelometer.

Figure 3.2b
The configuration of light source, detector, and sampling chamber for a typical, commercially available intergrating nephelometer.



SECTION FOUR ORIGIN AND DISPERSION OF ATMOSPHERIC PARTICULATES AND GASES AFFECTING VISIBILITY

Particulates and gases in the atmosphere can originate from natural or man-made sources. Table 1 includes the terms that are usually used to describe airborne particles; Table 2 shows the size range of typical atmospheric aerosols.

The ability to see and appreciate a visual resource is limited, in the unpolluted atmosphere, by light scattering of the molecules that make up the atmosphere. These molecules are primarily nitrogen and oxygen along with some trace gases such as argon and hydrogen. Other forms of natural aerosol that limit our ability to see are condensed water vapor (water droplets), wind-blown dust, and secondary aerosols.

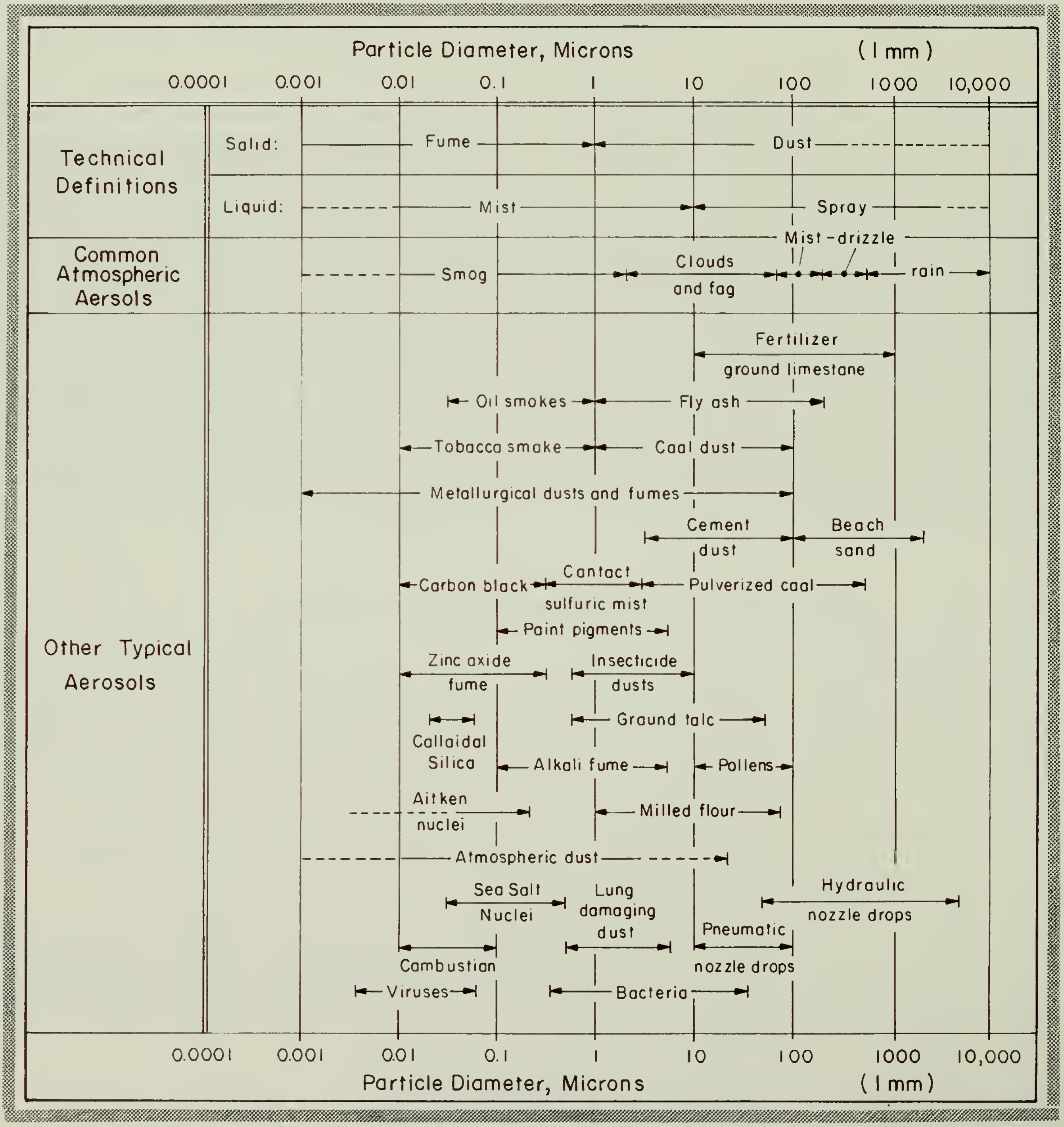
Secondary aerosols are airborne dispersions of particles formed by atmospheric reaction of gaseous "precursor" emissions. Figure 4.1 is a schematic summary of how gases are converted into aerosols of various sizes. The reactions are very complex and only in recent years have the physical processes been understood.

The gas to aerosol conversion process takes place by essentially three processes; condensation, nucleation, and coagulation. Condensation involves gaseous vapors condensing or combining with existing small nuclei, usually referred to as condensation nuclei. The small condensation nuclei may have their origin in sea salts or from combustion processes. Gases may also interact and combine with droplets of their own kind and form larger aerosols. This process is referred to as homogenous nucleation. Once aerosols are formed they can grow in size by a process called coagulation. In coagulation, particles essentially bump into each other and "stick" together. In each of these processes the interaction takes place via the electronic structure of the molecule or aerosol, and the subsequent formation of new particles results in a lower overall energy state.

Table 1
Definitions of Terms That Describe Airborne Particulate Matter

Particulate matter	Any material, except uncombined water, that exists in the solid or liquid state in the atmosphere or gas stream at standard condition
Aerosol	A dispersion of microscopic solid or liquid particles in gaseous media
Dust	Solid particles larger than colloidal size capable of temporary syspension in air
Fly ash	Finely divided particles of ash entrained in flue gas. Particles may contain unburned fuel
Fog	Visible aerosol
Fume	Particles formed by condensation, sublimation, or chemical reaction, predominantly smaller than 1μ (tobacco smoke)
Mist	Dispersion of small liquid droplets of sufficient size to fall from the air
Particle	Discrete mass of solid or liquid matter
Smoke	Small gasborne particles resulting from combustion
Soot	An agglomeration of carbon particles

Table 2
Typical Size Ranges of a Number of Aerosols Commonly Found in the Atmosphere



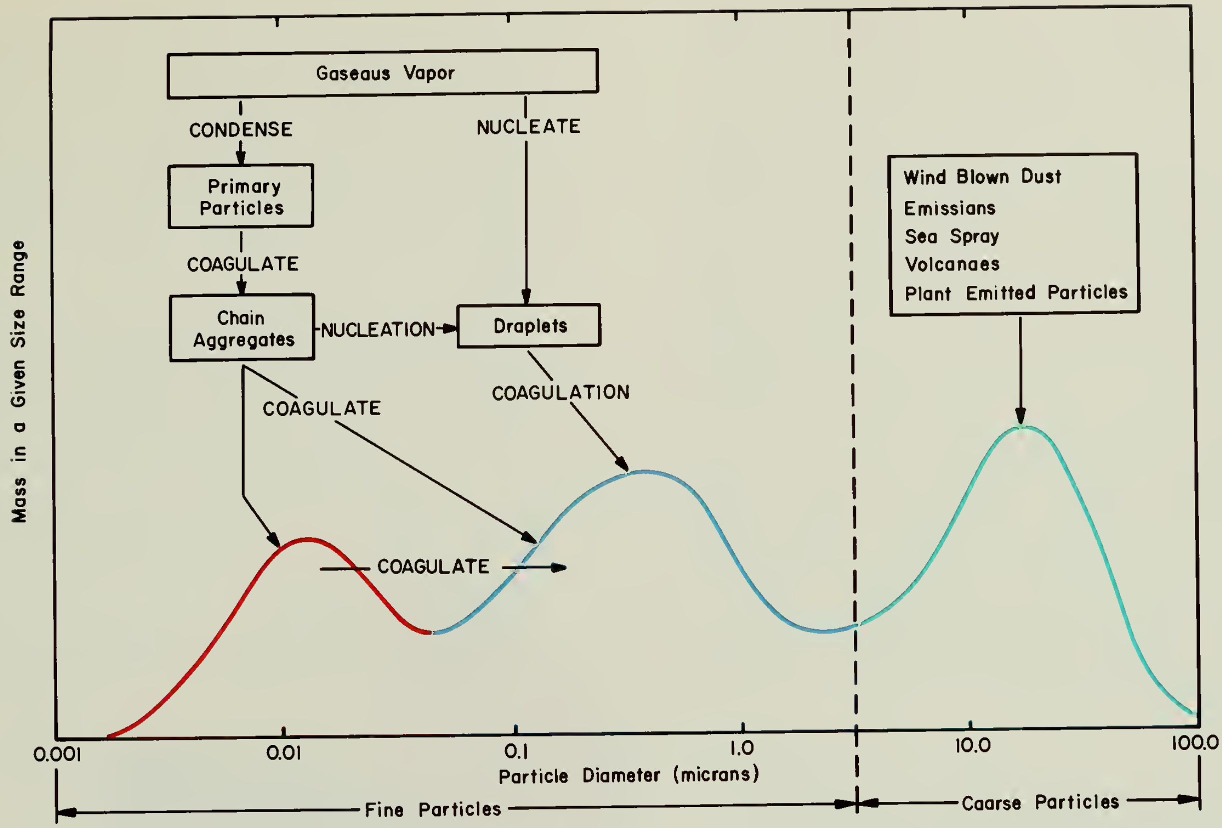


Table 3

Nationwide Emission Estimates, 1977
(10^6 Metric Tons/Year)

Source category	TSP	SO_x	NO_x	VOC
Transportation	1.1	0.8	9.2	11.5
Highway vehicles	0.8	0.4	6.7	9.9
Non-highway vehicles	0.3	0.4	2.5	1.6
Stationary fuel combustion	4.8	22.4	13.0	1.5
Electric utilities	3.4	17.6	7.1	0.1
Industrial	1.2	3.2	5.0	1.3
Residential, commercial, and institutional	0.2	1.6	0.9	0.1
Industrial processes	5.4	4.2	0.7	10.1
Chemicals	0.2	0.2	0.2	2.7
Petroleum refining	0.1	0.8	0.4	1.1
Metals	1.3	2.4	0	0.1
Mineral products	2.7	0.6	0.1	0.1
Oil and gas production and marketing	0	0.1	0	3.1
Industrial organic solvent use	0	0	0	2.7
Other processes	1.1	0.1	0	0.3
Solid waste	0.4	0	0.1	0.7
Miscellaneous	0.7	0	0.1	4.5
Forest wildfires and managed burning	0.5	0	0.1	0.7
Agricultural burning	0.1	0	0	0.1
Coal refuse burning	0	0	0	0
Structural fires	0.1	0	0	0
Miscellaneous organic solvent use	0	0	0	3.7
Total	12.4	27.4	23.1	28.3

Note: A zero indicates emissions of less than 50,000 metric tons per year

1) TSP: total suspended particulates
2) SO_x: sulfur dioxide and sulfur trioxide emissions
3) NO_x: nitrogen oxide and nitrogen dioxide emissions
4) VOC: volatile organic carbons

Figure 4.1

The origin or aerosol mass as a function of aerosol diameter. Gaseous vapor can convert into particles by the processes of condensation, coagulation, and nucleation. The origin of coarse particles, those with diameters larger than 2.5 microns, is primarily wind blown dust.

Table 3 summarizes the sources of man-made, or anthropogenic, emissions. The pollutants of primary concern to visibility reduction, because they are or become efficient light scatterers, are fine particulates, nitrogen dioxide, and sulfur dioxide gas. Sulfur dioxide gas is of interest because it can, under the right conditions, convert into a sulfate aerosol through the gas-to-particle mechanisms already discussed. Nitrogen dioxide, on the other hand, absorbs blue light as a gas; consequently it is, by itself, an important pollutant. Organic compounds are also of interest because they can contribute to the formation of sulfates and nitrogen dioxide and can form organic aerosols.

Once the gases and particulate matter are emitted from a source into the atmosphere, they are entirely responsive to meteorological conditions. Pollutant transport and transformation (gas-to-aerosol conversion) depend on wind speed and atmospheric stability, as well as solar radiation. An understanding of atmospheric stability is vital to understanding how pollutants are transported by the atmosphere. Atmospheric stability determines the movement of air parcels within the atmosphere as a whole. If air parcels are moving vertically up and down, the atmosphere is said to be

mixed and unstable. On the other hand, if an air parcel does not have vertical motion, it is said to be stable and usually is referred to as a stagnant air mass.

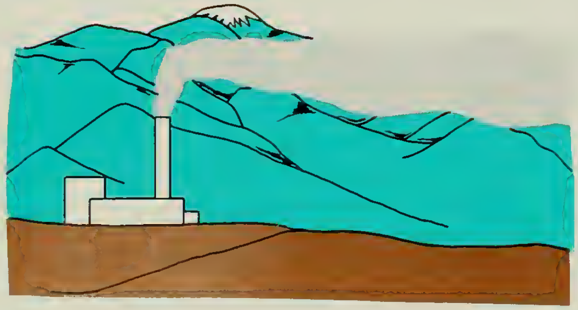
The amount of solar radiation that is allowed to heat the ground essentially determines whether the atmosphere is stable or unstable. The sun's radiation passes through the atmosphere, transferring little of its energy to air molecules or atmospheric aerosols. After passing through the atmosphere it strikes the earth where it is absorbed and converted into heat energy. The earth, in turn, heats the air near the ground. These warm air parcels then rise, allowing colder air parcels to move down near the earth. The cold air parcels are heated and the process continues. Under conditions where sufficient solar energy exists to heat the earth and in turn the air next to the earth, the result will be a well mixed and unstable atmosphere. Pollutants emitted into this type of atmosphere will be well mixed and will appear as a uniform haze. This condition is shown schematically in Figure 4.2a.

On the other hand, if there exists insufficient radiation to heat the earth, the air next to the earth becomes cooler than the air farther up in the atmosphere and a stable, non-mixing system results (inversion layer). Stable conditions usually occur at night and during winter months. During winter months there is not only less radiation heating the earth, but in some instances the white snow covering parts of the earth reflects radiation back into the atmosphere. Because of these compound effects it is possible to have stable or stagnant air for a week or more at a time. These conditions are usually referred to as stagnation periods or episodes.

When pollutants are emitted into a stable atmosphere usually one of two things will happen, depending on whether there is surface wind or not. If a wind is present, the emitted pollutants usually form a plume, as indicated in Figure 4.2b. If there are no surface winds or if pollutants are emitted into a stagnant air mass over periods of days, a condition schematically shown in Figure 4.2c can occur. A layer of haze forms near the ground and continues to build as long as the stagnation condition persists.

Whether the pollutants are transported from one location to another or trapped in a stagnant air mass, they will transform from gases to aerosols and from

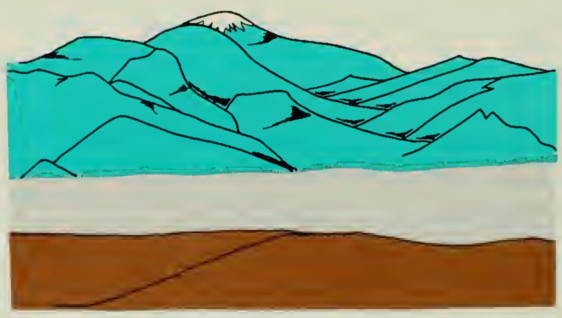
a.



b.

Figure 4.2a, b, and c

The three ways that air pollution can visually degrade a scenic vista. When there is sufficient sunlight to cause the atmosphere to become turbulent, pollutants emitted into the atmosphere become well mixed and appear as a uniform haze.



c.

This condition is shown in Figure 4.2a. On the other hand, during cold winter months the atmosphere becomes stagnant. Pollutants emitted during these periods will appear either as a coherent plume (Figure 4.2b) or as a layered haze (Figure 4.2c).

small to larger particles. As they transform, their ability to scatter and absorb light will change. Figure 4.3 shows a typical Grand Canyon light extinction distribution or budget that results from local sources as well as sources that had their origin hundreds of kilometers from the sampling site. Ammonium sulfate, $(NH_4)_2SO_4$, results from sulfur dioxide gas emissions from distant copper smelters and coal-fired power plants. As the sulfur dioxide is transported through the atmosphere it converts to an aerosol responsible for much of the atmospheric extinction. Organic carbon can have its origins from automobile hydrocarbon emissions and/or vegetation. Soot (elemental carbon) can come from diesels or from forest fires. Fine crustal material is from wind-blown dust, and because it is fine, it can be transported hundreds of kilometers. Coarse soil, on the other hand, is local in nature and is usually transported only a few kilometers.

Extinction budgets change depending on the origin of the air mass. At the Grand Canyon, for instance, the air tends to contain lower concentrations of man-made pollutants if the air originates from the north. It is very high in sulfate and organics if the air mass arrives at the Grand Canyon after passing over southern California, Arizona, and New Mexico. Figure 4.4 approximates origins of "clean" and "dirty" air masses for the Colorado Plateau Region.

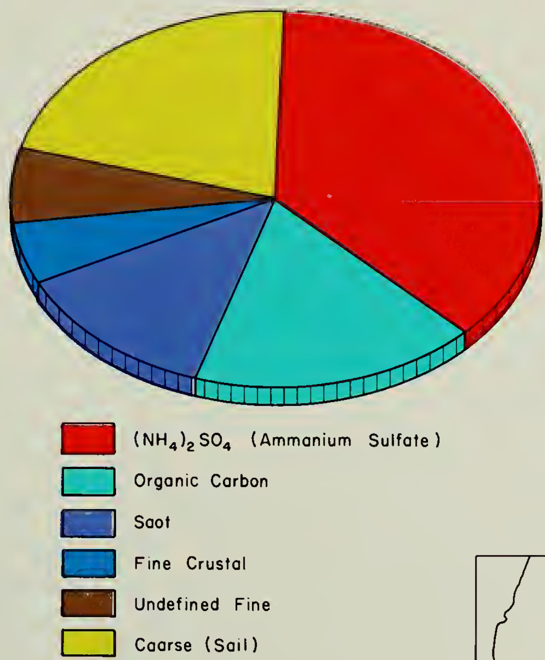


Figure 4.3
The relative amount of light extinction associated with various types of particulates. Ammonium sulfate is usually the largest single contributor to light extinction while soil-related particles also account for a large portion of visibility-reducing particulate matter.

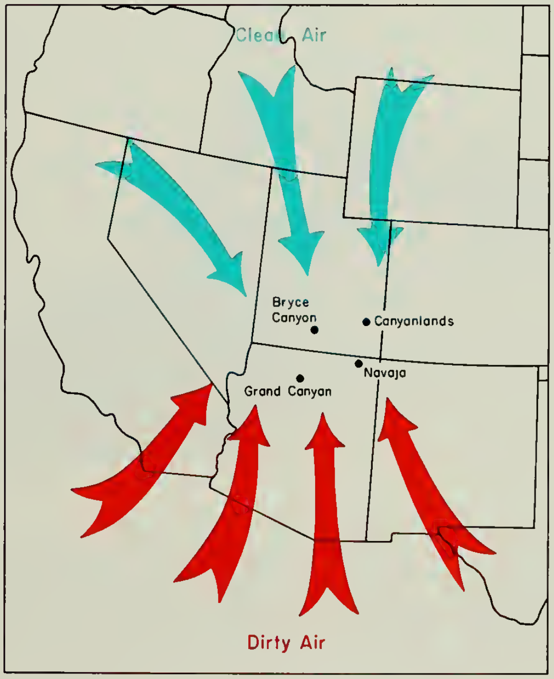


Figure 4.4
Origins of "clean" and "dirty" air in the Colorado Plateau area. If the air passes over southern California, Arizona, or New Mexico it tends to be dirty. Those air masses that originate from the north have a tendency to be far less polluted.

SECTION FIVE VISION THROUGH THE ATMOSPHERE

Visibility involves more than specifying how light is absorbed and scattered by the atmosphere. Visibility is a psychophysical process of perceiving the environment through the use of the eye-brain system. Important factors involved in seeing an object are outlined in Figure 5.1 and summarized below.

- Illumination of the overall scene by the sun. This includes illumination resulting from sunlight scattered by clouds and atmosphere as well as reflections by ground and vegetation.
- Target characteristics that include color, texture, form, and brightness.

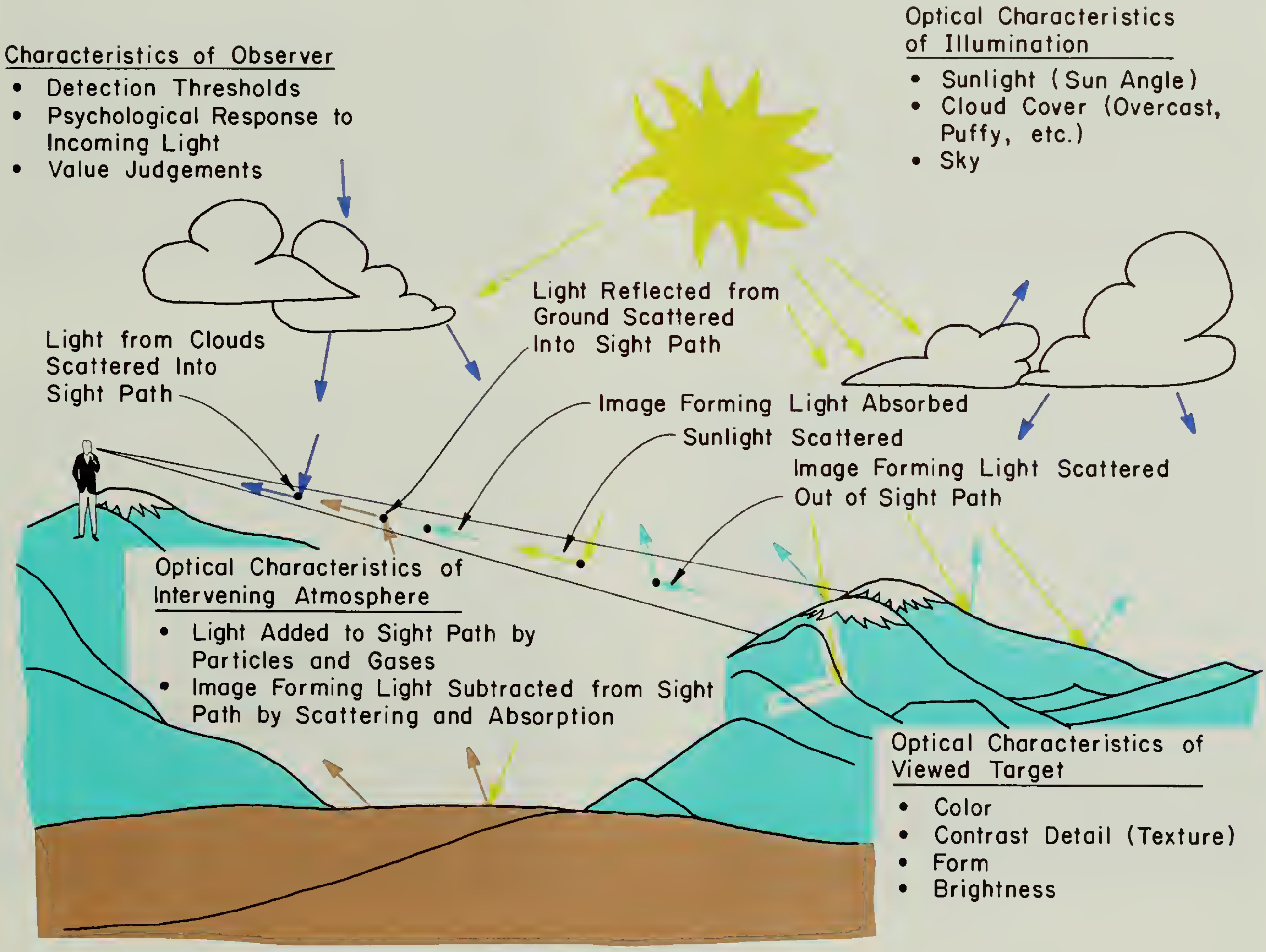


Figure 5.1
Important factors involved in seeing a scenic vista are outlined. Image-forming information from an object is reduced (scattered and absorbed) as it passes through the atmosphere to the human observer. Air light is also added to the sight path by scattering processes. Sunlight, light from clouds, and ground-reflected light all impinge on and scatter from particulates located in the sight path. Some of this scattered light remains in the sight path, and at times it can become so bright that the image essentially disappears. A final important factor in seeing and appreciating a scenic vista is the characteristics of the human observer.

- Optical characteristics of intervening atmosphere:
  i. image-forming information (radiation) originating from landscape features is scattered and absorbed (attenuated) as it passes through the atmosphere toward the observer, and
  ii. sunlight, ground reflected light, and light reflected by other objects are scattered by the intervening atmosphere into the sight path.
- Psychophysical response of the eye-brain system to incoming radiation.

It is important to understand the significance of the light that is scattered in the sight path toward the observer. The amount of light scattered by the atmosphere and particles between the object and observer can be so bright and dominant that the light reflected by the landscape features becomes insignificant. This is somewhat analogous to viewing a candle in a brightly lit room and in a room that would otherwise be in total darkness. In the first case the candle can hardly be seen, while in the other it becomes the dominant feature in the room.

The eye, whether it is looking at a vista or the candle in the room, detects relative differences in brightness rather than the overall brightness level. That is to say, the eye measures contrast between adjacent objects or between an object and its background. Contrast of an object is simply the percent difference between object luminance and its background luminance. The eye, shown in Figure 5.2, has a lens, an aperature to control the amount of light entering the eye (iris), and a detector, called the retina. Another type of instrument, the telephotometer, operates in much the same manner as a camera or the human eye. A camera operates in almost the same way except that the de-

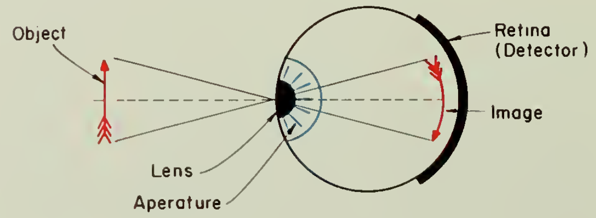


Figure 5.2
The human eye operates much like a photographic camera. It has a lens to focus an image on a very sensitive detector called the retina. Additionally the amount of light entering the eye is controlled by an aperature called the iris. The iris is the colored portion of the eye.

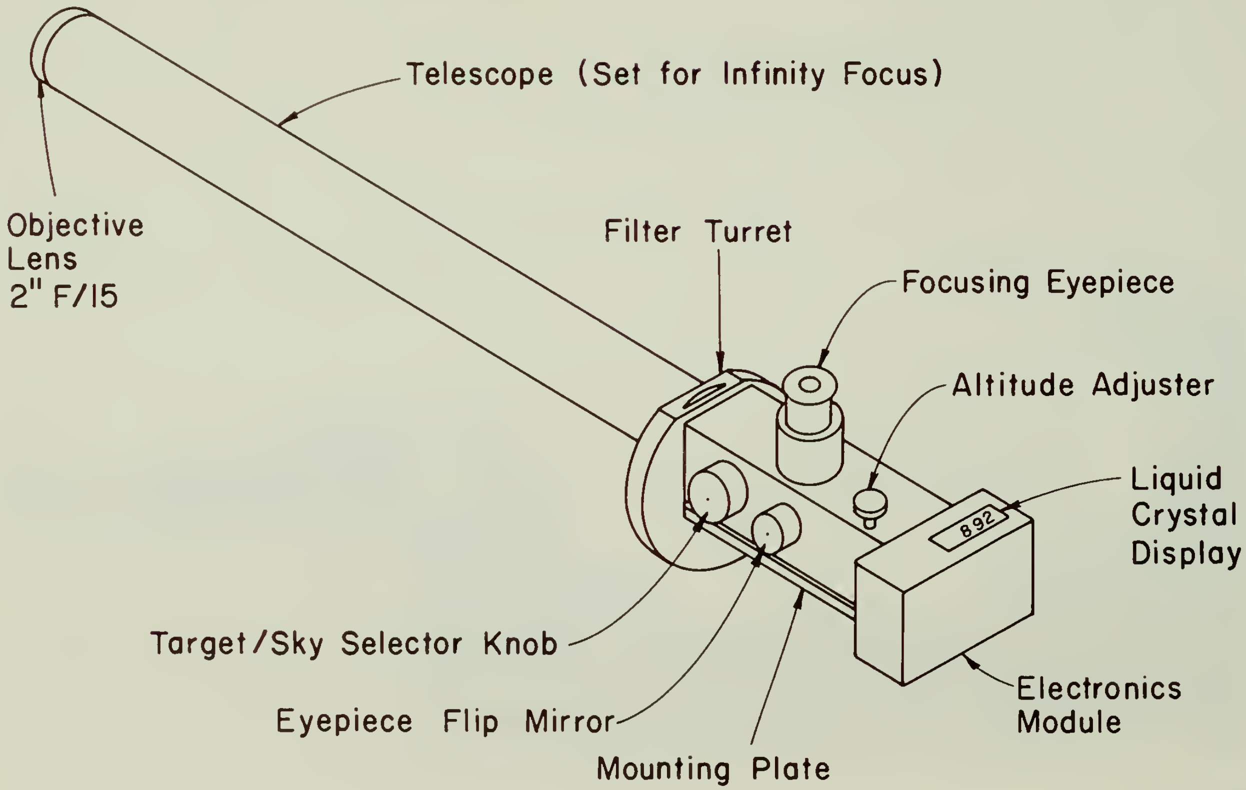


Figure 5.3
The telephotometer works much like the human eye. It also has a lens, detector system, and aperature. However, instead of the detector being connected to a complicated processor like the human brain, a telephotometer detector is connected to an electronic data storage device which allows specific information about visual air quality to be "data logged" for future processing.

tector is now photographic film instead of a retina. Figure 5.3 shows a schematic diagram of a telephotometer that uses a single detector capable of very precisely measuring the light coming from specific portions of a scene.

The camera can be an effective tool in capturing the visual impact that pollutants have on a visual resource. Figure 5.4a, b, c, and d show the effect that various levels of uniform haze have on the La Sal Mountains in Utah. These photographs were taken from Island in the Sky, Canyonlands National Park, which is about 50 km. due east of the La Sals. Sky-mountain contrasts are -0.46, -0.21, -0.07, and -0.04 while the associated atmospheric fine particulate concentrations

a. c.

b. d.

Figure 5.4a, b, c, d

The effect of regional or uniform haze on a Canyonlands National Park vista. The distant landscape feature is the La Sal Mountains. Atmospheric particulate concentrations associated with photographs a, b, c, and d correspond to near zero, 5 $\mu g/m^3$, 12 $\mu g/m^3$, and 16 $\mu g/m^3$.

in each case are below sensitivity of instrument, 5 $\mu g/m^3$ 12 $\mu g/m^3$ and 16 $\mu g/m^3$ respectively. Figures 5.5 and 5.6 show similar hazes of vistas at Mesa Verde and Bryce Canyon National Parks. The Chuska Mountains in Figure 5.5 are 95 km. away, with the contrast at -0.26. Navajo Mountain is 130 km. distant (Figure 5.6) and in this photograph the sky-mountain contrast is -0.08. This photograph should be compared with Figure Ia (page 2), a photograph of Navajo Mountain taken on a day in which the particulate concentration in the atmosphere was near zero.

Under stagnant air mass conditions aerosols can be ''trapped'' and produce a visibility condition usually referred to as layered haze. Figure 5.7 shows Navajo

Figure 5.5
Effects of uniform haze on the Chuska Mountains as seen from Mesa Verde National Park. The atmospheric particulate concentration on the day this photograph was taken corresponded to 1 $\mu g/m^3$.

Figure 5.6
Uniform haze degrades visual air quality at Bryce Canyon National Park. The 130 km. distant landscape feature is Navajo Mountain. Atmospheric particulate concentration on the day this photograph was taken is 3 $\mu g/m^3$.

Figure 5.7
Navajo Mountain as seen from Bryce Canyon, showing the appearance of layered haze. The pollutants are trapped in a stable air mass that extends from the ground to about half way up the mountain side.

Mountain viewed from Bryce Canyon National Park with a bright layer of haze that extends from the ground to about halfway up the mountain. Figure 5.8 is a similar example of layered haze but with the top portion of the mountain obscured. Figure 5.9 is a classic example of plume blight. In plume blight instances, specific sources such as those shown in Figure 5.10 emit pollutants into a stable atmosphere. The pollutants are then transported in some direction with little or no vertical mixing.

Figure 5.8
Photograph of Navajo Mountain similar to Figure 5.7 but with a suspended haze layer that obscures the top portion of the mountain.

Figure 5.9
Classic example of "plume blight." The thin, dark plume on Navajo Mountain results from a point source emitting particulate matter into a stable atmosphere.

Figure 5.10
An example of one kind of point source that emits pollutants into the atmosphere.

Figures 5.11, 5.12, 5.13, and 5.14 show other layered haze conditions that frequently occur at Grand Canyon and Mesa Verde. At Mesa Verde (Figure 5.14) much of the pollution comes from the Four Corners power plant, while at the Grand Canyon the sources have not been specifically identified.

Figures 5.15 and 5.16 show the appearance of plumes containing carbon. In both of these cases the pollutants are being emitted from forest fires. However, Figure 5.15 shows the appearance of a specific forest fire plume while Figure 5.16 shows the effect of viewing a vista through a concentration of particles

Figure 5.11
Pollutants trapped by an inversion layer in the Grand Canyon. During the winter months inversions are quite common in almost all parts of the United States.

Figure 5.13
Effects of inversion layer in Grand Canyon. In this case a cloud has formed within the canyon walls.

Figure 5.12
Another example of pollutants trapped in an air inversion layer at Grand Canyon.

Figure 5.14
Effects of layered haze trapped in front of the Chuska Mountains as viewed from Mesa Verde National Park. This condition occurs 30 to 40% of the time during winter months.

containing carbon. In this instance the vista is the north wall of the Grand Canyon as seen from the top of San Francisco Peaks, northern Arizona. Notice the overall "graying" and reduction of contrast of the distant scenic features. Remember that carbon absorbs all wavelengths of light and scatters very little. Thus the scene will always tend to be darkened.

Figure 5.17 shows the effects of illumination on the appearance of power plant plumes. The two plumes on the left are particulate plumes while the two plumes on the right consist of water droplets. The plume on the far right, which is illuminated by direct sunlight, appears to be white. The second, identical water droplet plume, which is shaded, appears dark. The amount

Figure 5.15
Forest fire plume exemplifying the appearance of carbon particles and demonstrating the effect of lighting. Where the plume is illuminated it appears gray, but identical particles in the shadow of the plume appear dark or almost black.

Figure 5.16
Example of how light-absorbing particles (in this case, carbon) affect the ability to see a vista. Carbon absorbs all wavelengths of light and generally causes a "graying" of the overall scene. North wall of the Grand Canyon as seen from the top of San Francisco Peaks, northern Arizona.

Figure 5.17
The effect of illumination on the appearance of a plume. The two plumes on the right are identical in terms of their chemical make-up. However, the far right plume is directly illuminated by the sun and the second from right is shaded. The first appears white and the second appears almost black.

Figure 5.18
The brown discoloration resulting from atmosphere containing nitrogen dioxide (NO_2) being shaded by clouds but viewed against a clear blue sky. Light scattered by particulate matter in that atmosphere can dominate light absorbed by NO_2, causing a gray or blue appearing haze (left side of photograph).

of illumination can have a significant effect on how particulate concentrations appear.

Figure 5.18 demonstrates how the effect of nitrogen dioxide gas (NO_2), in combination with varied background illumination, can combine to yield a very brown atmospheric discoloration. If a volume of atmosphere containing NO_2 is shaded and if light passes through this shaded portion of the atmosphere, the light reaching the eye will be deficient in photons in the blue part of the spectrum. As a consequence, the light will appear brown or reddish in color. However, if light is allowed to shine on, but not through, that same portion of the atmosphere, scattered light reaches the observer's eye and the light can appear to be gray in nature. Both of these conditions are shown in Figure 5.18. On the right side of the photo the mixture of NO_2 and particulates is shaded by clouds. The same atmosphere, illuminated because the cloud cover has disappeared, appears almost gray in the middle portion of the photograph.

Effects of illumination are further illustrated in Figures 5.19 and 5.20. Figure 5.19a is an easterly view from Dinosaur National Park while Figure 5.19b shows a view from the same observation point but

a.

b.

Figure 5.19a and b

Effects of illumination. Two vistas at Dinosaur National Monument, one (a) looking to the East and one (b) looking to the West. Both photographs were taken at 9:00 a.m., when the sun was low in the Eastern sky.

looking to the west. Both of these photographs were taken on a near rayleigh day. Figure 5.20a and 5.20b show how these views, or vistas, appear when obscured by a layer of haze. On the view to the east the haze layer appears white, but the same air mass, viewed in the opposite direction, has a dark gray appearance. This effect is entirely due to the geometry involved with the observer and the sun angle. The sun is low in the eastern sky. Consequently, the photons reaching the observer from the easterly haze layer have been scattered in the forward direction. Because the haze appears white in nature, we can conclude that the particles must be quite large in comparison to the wavelength of light. The assumption that the particles are large is further reinforced by their appearance to the west in Figure 5.20b. In this photograph the sun is behind the observer. In order for scattered photons to reach the observer they would have to be back-scattered from the particles. Because the haze appears dark we can conclude that there is very little back-scattering, which is consistent with the large particle hypothesis.

The angle at which the sun illuminates a vista or landscape feature (sun angle) plays another important

a.

b.

Figure 5.20a and b
Photographs similar to those in Figure 5.19 show how the vistas appeared on a day when pollutants were trapped under an inversion layer. In Figure 5.20a the haze appears white; In Figure 5.20b the identical haze is dark or gray. Because most of the light energy is scattered in the forward direction (white haze), it can be concluded that the particles must be quite large in comparison to the wavelength of light.

role. Figure 5.21 exemplifies this effect. The view again is from Island in the Sky, Canyonlands National Park, looking out over Canyonlands with its many colorful features toward the 50 km. distant La Sal Mountains. The first photograph in the figure shows how the canyon appears when it is in total shadow (6:00 a.m.). Each photograph shows a progressively higher sun angle until in Figure 5.21d the scene is entirely illuminated. In each case the air quality is the same. The only change is in the angle with which the sun illuminated the vista. There are primarily two reasons for the apparent change in visual air quality. First, at higher sun angles, there is less scattering of light by the intervening atmosphere in the direction of the observer. Second, the vista reflects more light; consequently more image-forming information (reflected photons from the vista) reaches the eye. The contrast detail and scene are enhanced.

Figure 5.21a, b, c, and d

Four photographs showing the effect of shifting sun angle on the appearance of a vista as seen from Island in the Sky, Canyonlands National Park. In each photograph the air quality is the same. In Figure 5.21a (6:00 a.m.) the sun angle-observer-vista geometry results in a large amount of scattered air light (forward scattering) added to the sight path, but minimal amount of imaging light reflected from the vista. Figure 5.21d (12:00 noon) shows just the opposite case. Scattered light is minimized and reflected imaging light is at a maximum.

SECTION SIX HUMAN PERCEPTION OF VISUAL AIR QUALITY

A major challenge in establishing visibility values is to develop ways of quantatively measuring visibility impairment as perceived by the human eye. There are really two components to quantification of visual impairment of a scenic resource: 1) the establishment of the level of air pollution that is just noticeable at an individual level and 2) a determination of the functional relationship between air pollution and perceived visual air quality.

The first goal is important when it is necessary to quantitatively specify how much emissions in a given atmospheric condition can be seen. The second object is important when trying to assess the societal value, whether it be social, psychological, or economical, that a population puts on clean air. The first step in assessing value is to understand the relationship between perceived changes in visual air quality and an appropriate physical parameter, such as vista contrast or atmospheric extinction. For example, if a visitor is willing to pay $5.00 for a given decrease in atmospheric extinction (air pollution) at the Grand Canyon, but is unwilling to pay that same amount for a similar decrease at some other park, is it because a) that person values the scenic resource differently at the two parks or b) the perceived change in visual air quality is different at the two parks? That is, at one park a given decrease in extinction can readily be seen, while at another that same decrease may go unnoticed.

Developing relationships between air pollution and visitor perception falls into two uniquely different categories. Air pollution can manifest itself either as layered or as uniform haze. Layered haze can be thought of as any confined layer of pollutants that results in a visible spectral discontinuity between that layer and its background (sky or landscape). Uniform haze exhibits itself as an overall reduction in air clarity. As discussed in Section 5, the classic example of a layered haze is a tight, vertically constrained, coherent plume (plume blight). However, as an atmosphere moves from a stable to unstable condition and a plume mixes with the surrounding atmosphere, the plume impact on visual air quality may manifest itself in an over-all reduction in air clarity (uniform haze) rather than as a layer of haze.

The eye is much more sensitive to a sharp demarcation in brightness or color than it is to a gradual change in brightness or color whether that change takes place in space or time. Layered haze falls into the first category, in that the layer of haze is observed at some specific time and against some background (sky or landscape element), while uniform haze falls into the second. Because changes in uniform haze usually take place over time periods of hours or days, an evaluation of visual air quality change resulting from a uniform haze requires a person to "remember" what the scene looked like before a given change in air pollution took place. An evaluation of the impact a uniform haze has on visual air quality requires identification of those elements of the total vista that are deemed important to visitor experience. On the other hand, a layered haze, if visible, could constitute impairment regardless of background features.

It is also important to point out that judgements of visual air quality as a function of air pollution, whether the pollution manifests itself as layered or uniform haze, might be made different by variations in sun angle, cloud cover, or landscape features.

Much work remains in the effort to quantify the incremental increase in air pollution that produces just noticable changes in perceived visual air quality (PVAQ). On the other hand, a good deal has been learned about the relationship between PVAQ and various visibility parameters for both layered and uniform haze.

A number of studies have established relationships between PVAQ and various physical variables for vistas similar to those shown in the eight photographs of Figure 6.1. It would be ideal to find one variable that represents the same perceived change in air quality, whether the background atmosphere were clean or dirty, whether the vista were near or far, or whether the haze were layered or uniform.

To address these questions a study was formulated that involved a visitor survey. Visitors to a number of national parks were asked to rate slides, on a scale of one (poor) to ten (good), that represented various levels of air quality. It was expected that sun angle, amount of snow cover, meteorological conditions, and

a.

c.

d.

b.

Figure 6.1a, b, c, d, e, f, g, and h

Examples of slides in studies of people's perceptions of visual air quality. Photos a and b are of the 50 km. distant La Sal Mountains as seen from Canyonlands National Park. Photo c is of the 96 km. distant Chuska Mountains as seen from Mesa Verde National Park. Photo d is of a forest fire plume as seen from Grand Canyon National Park. Photos e

e.

g.

f.

h.

and f are of Desert View (Grand Canyon National Park) as seen from Hopi Point. Photo g is also taken from Hopi Point but in the opposite direction as Desert View. The distant mountain (96 km.) is Mt. Trumbull. Photo h is of the 50 km. distant San Francisco Peaks as seen from Grand Canyon National Park.

other factors might affect ratings of visual air quality. Thus, a special effort was made to select slides that showed various air pollution levels under a number of atmospheric conditions. Specifically, a number of slides representing the best, worst, and intermediate levels of air quality were chosen to correspond to various cloud, snow cover, and sun angle conditions. These randomly ordered evaluation slides were preceded by ten preview slides. Preview slides were used to orient the observers to the full range of visual air quality conditions.

Park visitors were approached and asked if they would like to participate in a study designed to evaluate visual air quality in national parks. If they concurred, the visitors were seated in a trailer and given verbal instructions similar to the following paragraphs.

''I will first read some standardized instructions. This may seem a little stuffy, but it is important that everyone participating in these studies has the same information. Everyone is aware of the need for careful management of our natural resources. Increasing demands are being placed on our land, air, and water resources. These demands must be met, but we must also protect the quality of our natural environment.

''Visual air quality, or visibility, is the ability to see and appreciate a visual resource, such as an object, activity, scene, or atmospheric phenomenon. Visual resources should be seen clearly enough to be identified, and should appear sufficiently free of discoloration that their special natural, scenic, historic, or recreational values can be fully enjoyed. Visibility can be degraded by either natural or man-caused pollution sources; the resulting visibility degradation can result in either change in color or clarity of near and distant vistas.

''In this research we are trying to determine your perception of visual air quality in Canyonlands National Park. We greatly appreciate your help in this study.

''I am going to show you some color slides taken in the park during this past year. The scene is the same in every case, but weather conditions and other factors such as the amount of air pollution are somewhat different in each slide. You should look at each slide separately and try to judge the visual air quality represented at the time the slide was taken. You will notice that factors such as the time of day, clouds, ground cover, and weather conditions sometimes make the judgement difficult, but try to base your response on visual air quality.

''Slides will be shown one at a time. Please use the rating scale shown at the top of your response sheet to indicate your judgement for each slide. The scale extends from one, indicating that you judge the visual air quality to be very low (poor), to ten, indicating very high (good) visual air quality.

''Before you begin to rate scenes, I will quickly show you a few slides just to give you an idea of the kind of scenes on the one to ten scale, but do not write down any ratings for them. After the preview slides, I will ask you to rate the rest of the scenes. You should try to use the full range of the rating scale, and be sure to write down a number for each slide.

''Here are the preview slides. Just use these to get an idea of the kind of scenes you will be asked to judge.''

The Technician shows ten to twelve preview slides at a rate of about five seconds per slide, then continues:

''Now please rate each of the following scenes using the one to ten visual air quality scale. Slides will be shown rather briefly, but you will have plenty of time to judge each scene and write down your rating. From time to time I will announce which slide number we are on so you can keep your place on the rating sheet.''

Slides are shown at a rate of five to eight seconds per slide; slide numbers are announced for every fifth slide. After forty-eight slides have been shown the visitors are led into the room in front of the ''vista window,'' a window that allows them to evaluate a three dimensional scene that is very similar to the scenes they have just evaluated in the slide format.

The Technician continues:

''Now we would like to have you look out this window and judge the Visual Air Quality in the Park today. Please use the same ten point scale you used for your judgements of the slides. Write your rating in the space marked 'C' on your response sheet.

''Before you hand in your response sheet, would you please take a few moments to answer the questions on the last page. When you finish, hand your completed response sheet to [name] in the next room. He/she will answer any questions you may have about this research and your part in it.

''Thank you very much for taking the time to help us with the project.''

At the time of evaluation of the on-site three dimensional scenes, instrumental measurements of air quality were made and a slide of the scene was taken. Thus, at a later date this slide could be inserted into the set of evaluation slides and be evaluated by future visitors. In this way it is possible to establish a data base of actual three dimensional ratings as they relate to Perceived Visual Air Quality (PVAQ) of a three dimensional scene and the two dimensional scene represented by the slide.

The questionnaire completed by the participants established basic demographic data such as age, sex, rural or urban residence, educational level, and degree of park visitation. These categories were used in data analysis to test for rating variability which could be caused by demographic differences.

To address the accuracy with which the observers used the rating scale, fifteen identical control slides were mixed with evaluation slides. Calculations showed that if fifty ratings of the control slides were chosen at random from the total data set, the mean rating of different groups of fifty changed by less than 0.1 points, while the standard deviations varied by only 0.4. However, there is the possibility that, even though there may be some variability due to the observers' demographic backgrounds, a random selection would tend to average out of the differences. Thus an additional analysis involving the calculations of means and standard deviations of the control slides as a function of demographic background was carried

out. It was shown that regardless of educational level, age, sex, or location of residence, individuals judged visual air quality essentially the same; means and standard deviations varied by as little as 0.3.

To further assess any differences in perceptual responses of the different demographic groups represented, an analysis of the within and between group agreement in ratings of the evaluation slides was conducted. For the within group analysis, participants were successively divided into the various demographic sets (e.g., males-females, rural-urban-suburban, age groupings). Agreement between participants within each group was gauged by correlating each individual's ratings of the forty-eight evaluation slides against the mean ratings for each slide, based on the ratings by all members of that group. The average within group correlations (as a descriptive statistic) are reported for each group in Table 4. Agreement between groups was measured by intercorrelating the separate group means for the forty-eight slides within each demographic subset of the participants. The average between group correlation was 0.99, with the lowest correlation being 0.98. All reported correlation coefficients exceed the 99 percent level of statistical significance. More importantly, all coefficients are very high and positive, indicating very good agreement, both within and between demographic groups.

A most important result of these studies was the close agreement between on-site and slide ratings. Correlation between on-site and slide ratings was 0.94. ratings was 0.94. Statistical tests showed that in almost all cases there was not a significant difference between the window and slide ratings. Based on these studies it appears that there is good reason to expect that slides can provide a reasonable representation of actual scenes.

Because both within group and between group correlations are high, and because there is good agreement between on-site and side ratings it can be stated with some confidence that functional relationships between perception of visual air quality and physical variables derived from these studies are both reliable and accurate.

The one simple relationship that was repeated over and over was between average vista contrast and Perceived Visual Air Quality. For example, one portion of the study used the photographs shown in Figures 6.2 and 6.3. The figures show two vistas under clear sky conditions but with various levels of air pollution. In Figure 6.2 a 50 km. distant mountain range dominates the scenic vista, while in Figure 6.3 the distant mountain feature, which is the only scenic element that shows a visual effect from an increase in air pollution, takes up only four percent of the total scene. Yet when Perceived Visual Air Quality, which is the average of the one to ten ratings assigned to each slide by the park visitors, is plotted against the contrast of the most distant scenic element, a straight line relationship results for either scene. This relationship is surprising for the second scene because the distant feature is quite small. A representative relationship of the change in PVAQ evoked by a given change in contrast is shown by the red line in Figure 6.4.

Table 4
Analysis of Within and Between Group Agreement for Various Demographic Backgrounds of Observers

	Number of observations	Mean	Control slides Standard deviation	Evaluation slides Average correlation
Home				
Rural	129	4.8	1.5	0.85
Suburban	330	4.7	1.6	0.86
Urban	258	4.6	1.6	0.87
Age				
Under 18	42	4.8	1.8	0.83
18-24	114	4.9	1.5	0.88
25-34	221	4.8	1.5	0.87
35-44	106	4.7	1.6	0.85
45-54	84	4.4	1.6	0.85
55 +	149	4.6	1.5	0.85
Education				
under 12 years	44	4.6	1.7	0.82
High School	126	4.5	1.6	0.82
College-no. deg.	179	4.7	1.5	0.86
Bachelors	217	4.7	1.5	0.87
Post-Grad.	165	4.8	1.5	0.87
Sex				
Male	426	4.8	1.5	0.87
Female	305	4.5	1.6	0.85

a.

b.

c.

Figure 6.2a, b, and c

The appearance of one Canyonlands National Park vista under various air quality levels. The distant (50 km.) mountain range is the La Sal Mountains. Notice that the foreground features, because of the proximity to the observer and the bright color, show little change as air quality changes. The La Sal Mountains go from being very clear to almost disappearing. The sky-mountain contrast in Figure 6.2a is —0.39, for Figure 6.2b, —0.26b, and for Figure 6.2c, —0.23.

a.

b.

c.

Figure 6.3a, b, and c

Mt. Trumbull, 96 km. distant, as seen from Grand Canyon National Park. Impairment is from a uniform haze. The sky-mountain contrasts for the three photographs, going from best to worst, are: —0.32, —0.29, and —0.15.

Because visitors see a visual resource under a variety of atmospheric conditions it is important to determine the effect that cloud cover or changes in sun angle will have on the sensitivity of a vista to changes in contrast. Surprisingly, the answer is "None!" Figure 6.4 also shows how a PVAQ versus contrast curve changes when sun angle is changed or cloud cover is added. In both cases the overall ratings are higher but the slopes of the curves, representing the sensitivities, remain the same. The photographs of Figure 6.5 show the same two vistas under different sun angle conditions; the photographs of Figure 6.6 show the La Sal Mountains in the presence of cumulus clouds. When sun angle is changed, the foreground features are illuminated and their color enhanced. Changing either sun angle or cloud cover results in an increase in scenic beauty and thus an increase in the average PVAQ ratings. It is emphasized, however, that the sensitivity of the vista-to-contrast-change is not altered. This means that visitors to this type of vista would be as sensitive to air pollution changes whether they came in the morning or afternoon, or whether there were clouds present or the sky were cloud free.

This linear relationship appeared consistent for all scenes as long as each scene had one specific scenic element that changed as a function of air pollution. Notice in the photographs of Figure 6.3 that the foreground features remain unchanged even though the visual air quality or contrast of the distant scene changes dramatically. The observers judging visual air

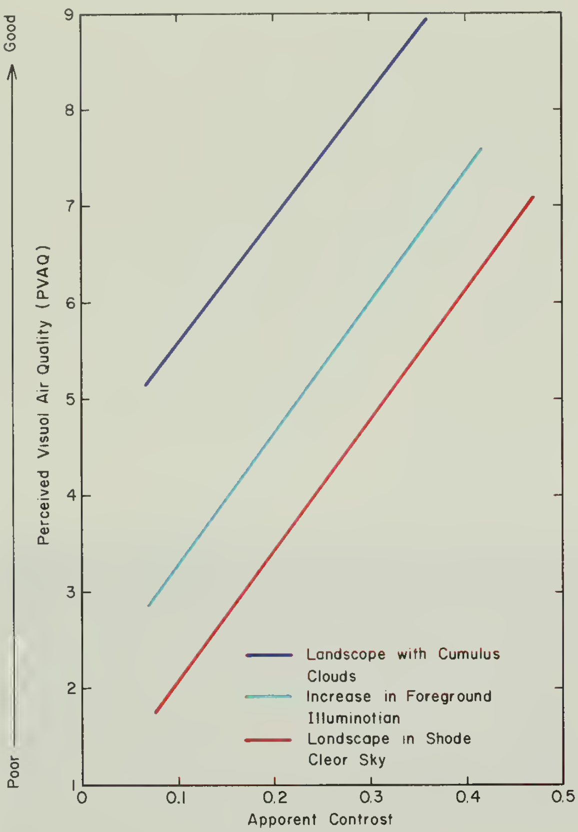


Figure 6.4
Plot of judgements of perceived air quality (PVAQ) as a function of apparent vista contrast of most distant landscape feature for a typical scene. The red line shows the linear relationship between these two variables where the scene is shaded from sunlight. The green line shows a similar relationship of the same vista but in direct sunlight. The blue line shows the relationship when cumulus clouds are present. Notice that the slopes of the PVAQ contrast lines do not change The sensitivity of an observer to visibility haze is independent of sun angle and meterological conditions.

Figure 6.5a and b
Mt. Trumbull as viewed from Hopi Point under two different lighting conditions. Foreground features change dramatically but studies show that the sensitivity of the vista to air pollution impact remains unchanged.

quality appear to "key in" on the scenic element that is most sensitive to changes in air pollution. The visual sensitivity of an observer to increases in air pollution is represented by the slope of the PVAQ versus contrast curve.

An increase in vista color exists as the one common denominator between the effects that sun angle, meteorological conditions, and air pollution have on perceived visual air quality. If vista color increases as a result of decreased air pollution, changing sun angle, or meteorological conditions, then the PVAQ increases. This does not mean that other perceptual clues, such as change in contrast detail or texture, should be ruled out as being important to PVAQ. However there does not appear to be a systematic relationship between texture and PVAQ or contrast detail and PVAQ.

The effect of changing sun angle on color was further investigated using scenes similar to those shown in Figure 5.21. When the scene was in full shadow the lowest PVAQ was evoked. As the sun rose in the sky, illuminating the vista and thus increasing its color, PVAQ also increased. This increase in PVAQ continued until the scene was fully illuminated (approximately noon) and then remained constant through the rest of the day (see Figure 6.7). These results support the idea of color change and PVAQ.

There does appear to be a simple linear relationship between PVAQ and other visibility parameters. One variable of particular interest is the particulate mass concentration. Particulate mass concentration is a direct measure of the amount of pollution in the atmosphere. The relationship between particulate

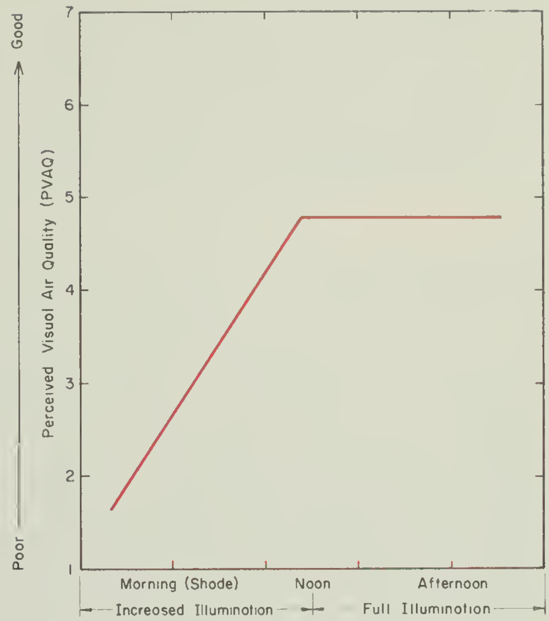
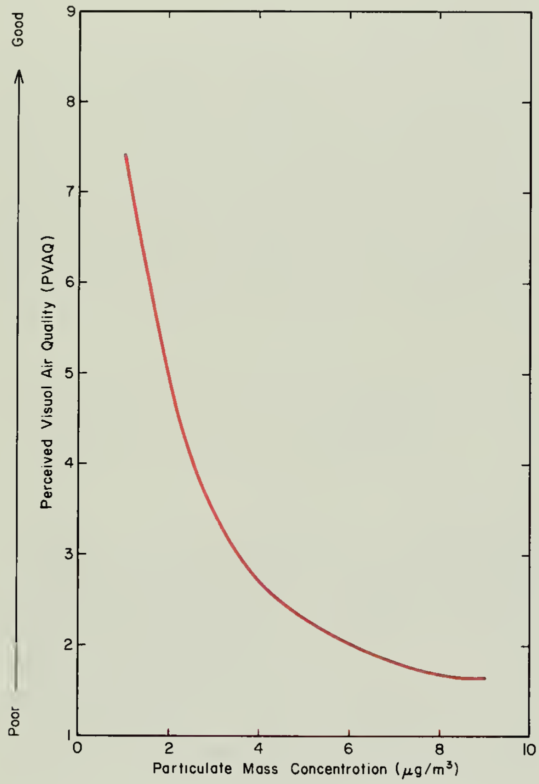


Figure 6.7
Perceived visual air quality plotted as a function of sun angle. During early morning hours the vista is shaded from sunlight, and color saturation of the scene is low. As the sun rises in the sky the scene moves from shade into direct illumination and becomes saturated with color. Judgements of visual air quality increase over this time period until the scene is fully illuminated. It then remains constant during afternoon hours.

Figure 6.6a and b
La Sal Mountains, showing the effect of changes in sun angle as well as the visual effect of cumulus clouds.

mass concentration and PVAQ is shown in Figure 6.8. Notice the non-linear nature of the relationship. A given change in mass concentration results in a much larger change in PVAQ when the air is clean than when it is dirty.



The effect of mass concentration on PVAQ is further illustrated by Figure 6.9. This graph shows the change in PVAQ resulting from a given increase in air pollution as a function of distance. First, a specified amount of air pollution increase has as much greater effect on PVAQ when the vista is seen in a clean atmosphere; secondly, there is an observer target distance that is perceptually most sensitive to air pollution increases. In relatively clean areas like the Grand Canyon, this distance is sixty to one hundred kilometers. In the East, where the atmosphere is already quite polluted, the most sensitive distance is closer to ten kilometers.

The above comments were with respect to vistas that contained certain scenic elements which are substantially more sensitive to air pollution change than the rest of the scene. For more complicated scenes it appears that the PVAQ varies as a function of the contrast change of each scenic element weighted in proportion to the area subtended by that element and to the inherent scenic beauty of each scenic feature. However, in general the above conclusions hold for these scenes as well.

Figure 6.8
In contrast to the very simple relationship between perceptions of visual air quality and vista contrast, perceived visual air quality plotted against particulate concentration shows a very non-linear relationship.

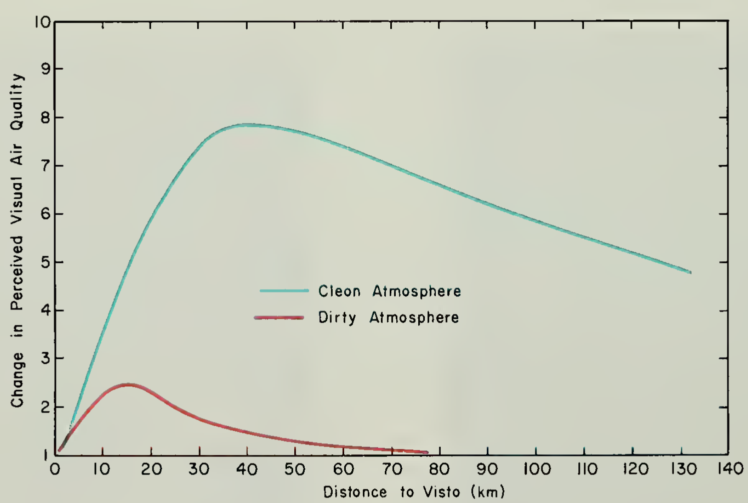


Figure 6.9
Relationships between perceived visual air quality (PVAQ) and vista distance for different levels of air quality. The red line shows the decrease in perceived visual air quality of a hypothetical vista as a result of adding a small amount of particulate matter to a "clean" atmosphere as a function of distance to the vista. The green curve is similar in nature but shows perceived changes in air quality when the atmosphere is already "dirty." Most importantly the graph shows that vistas viewed in a clean atmosphere are many more times sensitive to an incremental change in air pollution than when viewed under more impaired conditions, and secondly, there is a vista-observer distance that will result in a perceptual sensitivity that is greater than for any other distance.

Layered haze, whether it appears as a coherent plume or as a layer of pollutants trapped near the ground, is recognized by an abrupt change in color between itself and some background. Haze layers can be lighter or darker than the background sky, and under the right lighting conditions can also have a brown coloration. Figure 6.10 shows examples of three different haze layers. Figure 6.10a shows a white coherent plume over Navajo Mountain; Figure 6.10b shows a dark plume that just obscures the mountain top; Figure 6.10c shows a trapped haze layer that obscures approximately half of Navajo Mountain.

a.

b.

c.

Figure 6.10a, b, and c

Three ways in which air pollutants can manifest themselves as layered haze. Figure 6.10a shows a white plume positioned over Navajo Mountain as seen from Bryce Canyon National Park. Figure 6.10b shows a dark plume that just obscures the mountain top; Figure 6.10c is a dark haze layer that results from pollutants being trapped in a ground inversion layer.

Slides similar to those shown in Figure 6.10 were used in studies to determine individuals' perceptions of layered haze. Results of these studies are summarized in Figure 6.11; it should be kept in mind that a plume with a contrast of 0.02 to 0.05 is visible. The results indicate that plumes, when positioned in the sky in such a way as to not obscure the vista, have a minimal impact on Perceived Visual Air Quality (PVAQ). However, dark plumes were rated lower or perceived to have a greater impact on visual air quality than light colored plume, whether dark or light, obscurred more and more of the vista, the ratings went down. A plume or haze layer with a sky-haze contrast of 0.3 is perceived to be worse if it obscures two thirds of the mountain than if it obscures only one third of the scenic element.

It should be pointed out that there did not appear to be a simple relationship between any of the candidate physical varaibles that relate to visibility and Perceived Visual Air Quality (PVAQ). Much work remains to pacts of layered haze in such a way as to be representative of how humans perceive layered haze visual impairment.

Additionally, little work has been done on the amount of air pollution required to evoke just noticeable differences in air pollution. These areas remain open topics, ripe for innovative research efforts of the future.

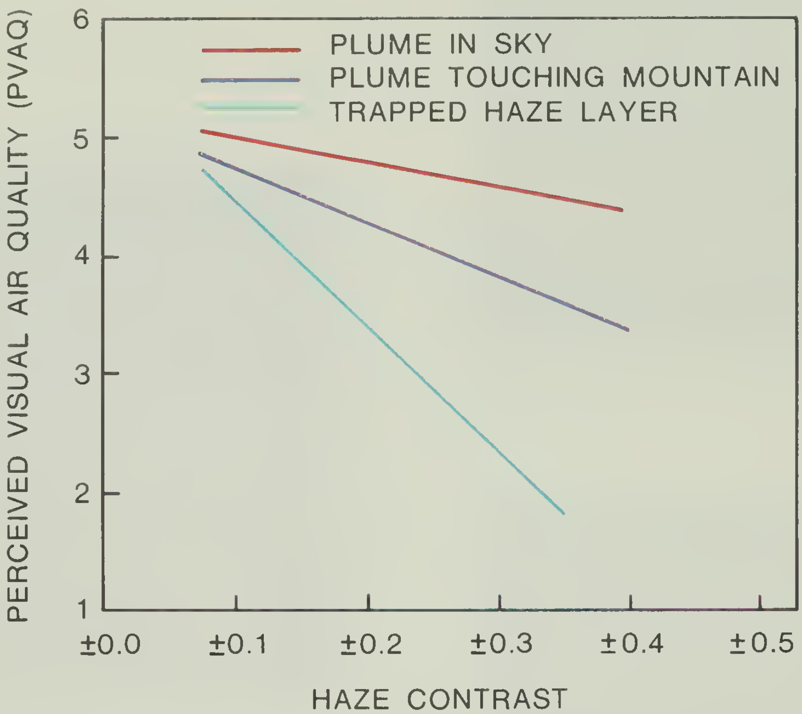


Figure 6.11

Summarization of the results of the layered haze perception studies. The red line shows the relationship between Perceived Visual Air Quality (PVAQ) and plume contrast for a white plume placed in the sky in such a way as to not touch any portion of the scenic vista. There is little change in PVAQ as plume contrast increases. The blue line and green line suggest the relationship between PVAQ and layered haze contrast for a plume just obscuring the mountain top and for a haze layer obscuring the lower one half of the mountain respectively. As haze obscures more of the mountain, the effect that a specific pollution level has on PVAQ is increased. This is indicated in Figure 6.11 by the increased slope of the blue line over that of the red line.

Glossary of Terms

Glossary of Terms

absorption coefficient: Measure of the ability of particles to absorb and scatter photons from a beam of light; a number that is proportional to the number of photons removed from a sight path per unit length. See sorption.

aerosol: A dispersion of microscopic solid or liquid particles in a gaseous medium. Smoke and fog are aerosols.

air light: The light from sun and sky which is scattered into the eyes of the observer by the air which lies directly between the observer and the viewed object.

air parcel: A volume of air that tends to be transported as a single entity.

anthropogenic: Produced by human activities.

attenuation: The diminuation of a quantity. In the case of visibility, attenuation or extinction refers to the loss of image forming light as it passes from an object to the observer.

bimodal distribution: A plot of the frequency of occurrence of a variable versus the variable is a bimodal distribution if there are two maxima of the frequency of occurrence separated by a minimum. See mode.

budget: See light extinction budget.

coagulation: The process by which small particles collide with and adhere to one another to form larger particles.

condensation: The process by which molecules in the atmosphere collide and adhere to small particles.

condensation nuclei: The small nuclei or particles with which gaseous constituents in the atmosphere (e.g. water vapor) collide and adhere.

diffraction: Modification of the behavior of a light wave resulting from limitations of its lateral extent by an obstacle. For example, the bending of light into the ''shadow area'' behind a particle.

diffusion: A process by which substances, heat, or other properties of a medium are transferred from regions of higher concentration to regions of lower concentration.

extinction: The attenuation of light due to scattering and absorption as it passes through a medium.

haze: An atmospheric aerosol of sufficient concentration to be visible. The particles are so small that they cannot be seen individually, but are still effective in visual range restriction. See visual range.

homogenous nucleation: Process by which gases interact and combine with droplets made up of their own kind. For instance, the collision and subsequent adherence of water vapor to a water droplet is homogenous nucleation. See nucleation.

hydrocarbons: Compounds containing only hydrogen and carbon. Examples: methane, benzene, decane, etc.

hygroscopic: Readily absorbing moisture, as from the atmosphere.

integrating nephelometer: An instrument which measures the amount of light scattered (scattering coefficient).

inversion, temperature: See temperature inversion.

isotropic: A situation where a quantity (or its spatial derivatives) are independent of position or direction.

isotropic scattering: The process of scattering light equally in all directions.

light extinction budget: The percent of total atmospheric extinction attributed to each aerosol and gaseous component of the atmosphere.

long path measurement: An atmospheric measurement process that is made over distances in excess of a few hundred meters.

micron: a unit of length equal to one millionth of a meter; the unit of measure for wavelength.

mode: The maximum point in a plot of the frequency of occurrence of a variable versus the variable.

nitrogen dioxide: a gas (NO_2) consisting of one nitrogen and two oxygen atoms. It absorbs blue light and therefore has a reddish-brown color associated with it.

NO_2: See nitrogen dioxide.

nucleation: Process by which a gas interacts and combines with droplets. See homogenous nucleation.

Perceived Visual Air Quality (PVAQ): An index that relates directly to how human observers perceive changes in visual air quality.

photometry: Instrumental methods, including analytical methods, employing measurement of light intensity. See telephotometer.

photon: A bundle of electromagnetic energy that exhibits both wave-like and particle-like characteristics.

plume blight: Visual impairment of air quality that manifests itself as a coherent plume.

point source: A source of pollution that is point-like in nature. An example is the smoke stack of a coal-fired power plant or smelter. See source.

polar nephelometer: An instrument that measures the amount of light scattered in a specific direction. See integrating nephelometer.

percursor emissions: Emissions from point or regional sources that transform into pollutants with varied chemical properties.

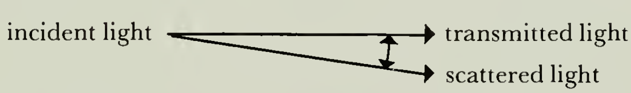
PVAQ: See Perceived Visual Air Quality.

Rayleigh scattering: The scattering of light by particles much smaller than the wavelength of the light. In the ideal case, the process is one of a pure dipole interaction with the electric field of the light wave.

relative humidity: The ratio of the partial pressure of water to the saturation vapor pressure, also called saturation ratio; often expressed as a percentage.

scattering (light): An interaction of a light wave with an object that causes the light to be redirected in its path. In elastic scattering no energy is lost to the object.

scattering angle: The angle between the direction of propagation of the scattered and incident light (or transmitted light):



scattering coefficient: Measure of the ability of particles to scatter photons out of a beam of light; measured in number proportional to the amount of photons scattered per distance.

scattering cross section: The extinction coefficient per particle, with units cm^2/particle.

secondary aerosols: Aerosol formed by the interaction of two or more gas molecules and or primary aerosols.

SO_2: See sulfur dioxide.

sorption: A class of processes by which one material is taken up by another. Absorption implies the penetration of one material into another; adsorption involves a surface phenomenon. See absorption.

source: In atmospheric chemistry, the place, places, group of sites, or areas where a substance is injected into the atmosphere. Can include point sources, elevated sources, area sources, regional sources, multiple sources, etc.

spectral: An adjective implying a separation of wavelengths of light or other waves into a spectrum or separated series of wavelengths.

stable air mass: An air mass which has little vertical mixing. See temperature inversion.

stagnant: Referring to meteorological conditions which are not conducive to atmospheric mixing.

stagnation episodes: See stagnation periods.

stagnation periods: Lengths of time during which little atmospheric mixing occurs over a geographical area, making the presence of layered hazes more likely. See temperature inversion.

sulfates: Those aerosols which have origins in the gas-to-aerosol conversion of sulfur dioxide; of primary interest are sulfuric acid and ammonium sulfate.

sulfur dioxide: A gas (SO_2) consisting of one sulfur and two oxygen atoms. Of interest because sulfur dioxide converts to an aerosol which is a very efficient light scatterer. Also can convert into acid droplets consisting primarily of sulfuric acid.

sun angle: Refers to the angle of the sun above the horizon of the earth.

telephotometer: An instrument that measures the brightness of a specific point in either the sky or vista.

temperature inversion: In meteorology, a departure from the normal decrease of temperature with increasing altitude such that the temperature is higher at a given height in the inversion layer than would be expected from the temperature below the layer. This warmer layer leads to increased stability and limited vertical mixing of air.

transmissometer: An instrument which measures the amount of light extinction over a specified path length.

unstable air mass: An air mass which is vertically well mixed. See also stable air mass, temperature inversion.

visual range: The distance at which a large black object just disappears from view.

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